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Laser-GMA Hybrid Pipe Welding System

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14. ABSTRACT
The combination of laser welding with conventional gas metal arc welding technology offers substantial increases in production rate of joining pipe through single-pass joining compared to multi-pass techniques that are commonly used. The hybrid process has been examined and developed for this application, and the process has been qualified through the American Bureau of Shipping for a wide range of pipe schedules. A system to realize this application has been specified, designed, built, and implemented in General Dynamics NASSCO Shipyard, and been subjected to a seven month evaluation on the production floor. Lessons learned have been documented to benefit future efforts. Fifteen actual production pipe spools were manufactured using the system.

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EXECUTIVE SUMMARY

The combination of laser welding with conventional gas metal arc welding technology offers substantial increases in production rate of joining pipe through single-pass joining compared to multi-pass techniques that are commonly used. The hybrid process has been examined and developed for this application, and the process has been qualified through the American Bureau of Shipping for a wide range of pipe schedules. A system to realize this application has been specified, designed, built, and implemented in General Dynamics NASSCO Shipyard, and been subjected to a seven month evaluation on the production floor. Lessons learned have been documented to benefit future efforts. Fifteen actual production pipe spools were manufactured using the system.

In addition to 17 publications, presentations, and demonstrations to aid in the transitioning of this technology, the efforts by the project have led to the following accomplishments:

- First qualification of hybrid laser welding by the American Bureau of Shipping in the U.S.
- First demonstration of hybrid laser welding in a U.S. shipyard.
- First production components hybrid welded in a U.S. shipyard.
- First hybrid welded components installed on a U.S. ship (T-AKE 6 and T-AKE 7).
- The basis of the hybrid pipe welding system specified by ARL Penn State and produced by Wolf Robotics was used for another similar system later ordered by a major heavy equipment manufacturer in the U.S. Thus, the effort was uncommon in that portions of the technology developed during the program were directly transitioned to U.S. industry.

Even when the additional time is spent to achieve proper fit-up for hybrid welding is considered, the estimated savings are substantial, and range from 23% to 49% savings in overall joining time based on data collected on actual production pipe spools. With more than 47,000 hours per year spent in joining pipe per year, the potential cost savings are significant. Additional process improvements would certainly be realized as the technology matures and would result in additional savings. Reductions in filler wire consumption and the attendant reductions in hazardous weld fume emissions would also be substantial.

INTRODUCTION

It has been nearly a quarter of a century since researchers first conceived of combining a conventional welding arc with a laser beam in a hybrid process [1,2], but only recently has laser-GMA hybrid welding begun to be utilized in industrial applications.

Laser beam welding (LBW) offers relatively high welding speed and high penetration compared to conventional arc-based joining processes. Unfortunately, due to the small spot size typically utilized in LBW, it has limited success in certain welding applications due to an inability to provide adequate reinforcement (i.e. filler material) and due to poor gap bridging capabilities. Consequently, laser beam welding requires high precision during edge preparation and setup, an added cost during manufacturing operations. Additionally, the focussed energy of the laser beam results in a narrow heat affected zone (HAZ) that can lead to steep spatial and temporal thermal gradients that can result in brittle microstructures.

In contrast, conventional Gas Metal Arc Welding (GMAW) offers the ability to easily add reinforcement sufficient to bridge gaps in the joint by introducing filler metal to the process. The composition of the filler materials can be customized to produce improved material properties. The additional heat results in reduced cooling rates, which can lead to improved ductility. However, the high heat associated with the process can also cause undesirable distortion or buckling, and the nature of the process prevents deep penetration welds. As a result, thick sections often require multiple weld passes.

In certain applications these shortcomings can be overcome by combining the LBW and GMAW processes. Not only is this helpful in providing reinforcement, accommodating gaps, and reducing weld-head positioner tolerance requirements while maintaining deep penetration than standard arc welding [3], but it has also been known to enable operation at even greater welding speeds and provide an improved weld microstructure upon cooling [4]. Additionally, the combination of LBW and GMAW may significantly reduce overall weld time in thick sections by joining in a single pass what would require multiple passes using conventional techniques. The marriage of LBW and GMAW for joining thick sections opens up numerous opportunities to tailor the process through variations in both process parameters and joint design.

In December 2004, this project was initiated to develop a hybrid laser-GMA pipe welding system and install and demonstrate it at General Dynamics National Steel and Shipbuilding Company (NASSCO). Throughout the development of the processing parameters and the system design, interim results have been presented through various conference and publications (see Appendix D and bibliographic references 5–8). In March 2007, the final system was delivered to the shipyard for a seven month demonstration and evaluation in their pipe welding shop. Numerous accomplishment were achieved during the project, including: (1) hybrid welding parameters were produced for joining pipe/fittings of various schedules, (2) an automated hybrid pipe welding system was specified, designed, and built, (3) the hybrid pipe welding technology was qualified for use by the American Bureau of Shipping, and (4) NASSCO operators produced 15 production pipe spools using the hybrid pipe welding system.

This report summarizes the effort, and is outlined as follows:

- Provide background that justifies the effort.
- Review the project objectives and outline the strategy to accomplish them.
- Discuss the hybrid pipe welding system specifications developed by ARL Penn State, outline how the system integrator was selected, and provide an overview of the final system design.
- Outline experiments developed and undertaken during determination of suitable process parameters and system design, and discuss results.
- Discuss the final system installation at GD NASSCO shipyard.
- Present a cost-benefit analysis.
- Present lessons learned during implementation for production and recommendations for improving the system and for future work.
- Summarize accomplishments of the project and discuss conclusions.

Appendices provide the system specification that were released for bid, a portion of the training manual that provides an overview of the final system architecture, several NASSCO reports that includes an overview of pipe welding parameters that were qualified by the American Bureau of Shipbuilding (ABS), and a summary of production pipe that was produced with the system, and a list of the publications that resulted from the work.

BACKGROUND

Welding of pipe represents a significant cost in the construction of tankers and other ships. Though much welding of pipe must occur *in situ* on board the ship, as much pipe as possible is rolled in a pipe shop and manually welded in the downhand position. Figure **1** illustrates a current joining technique employed at the NASSCO shipyard. In the figure, the pipe is fixtured to a rotary positioner that rotates the tack welded pipe spool beneath the arc weld torch, and the torch is manually manipulated by the operator. Conventional welding techniques, Gas Tungsten Arc Welding (GTAW), Flux Core Arc Welding (FCAW), and GMAW, are all employed for the joining operations.

Figure **1**. Photograph of the conventional pipe welding process.

At NASSCO, the steel pipe ranges in thickness from 5 to 12.7 mm (0.25 to 0.5 inch). In all cases, producing an adequate joint requires the execution of multiple weld passes. Figure **2** illustrates the top surface of such a joint, and Figure 3 shows a cross section.

Figure **2**. Close-Up photograph of multipass pipe weld.

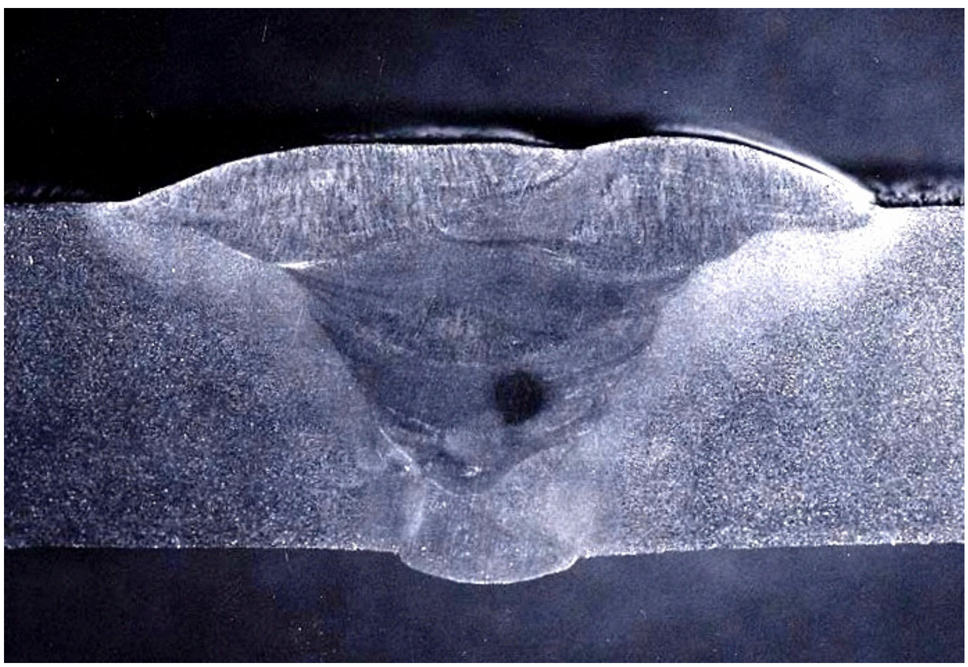

Figure **3**. Cross section of conventional multipass pipe weld with 12.7 mm (0.5 in) thickness.

To help determine potential savings in converting to a single-pass hybrid weld, a detailed investigation was undertaken to assess current practice and estimate potential cost savings [5]. A time study was conducted to determine the time spent on each of the various operations used to join a pipe to a fitting. It was determined that the joining process averages up to 100 minutes for

4 inch diameter pipe, and up to 300 minutes for 30 inch diameter pipe (total time). The multipass conventional weld portion of the process contributes significantly to this time because joining pipe to fitting requires 2–7 conventional arc welding passes at 0.12–0.25 m/min (5–10 ipm) weld travel speed. A sample of the results for an open root joint over a range of pipe diameters is shown in Figure **4**.

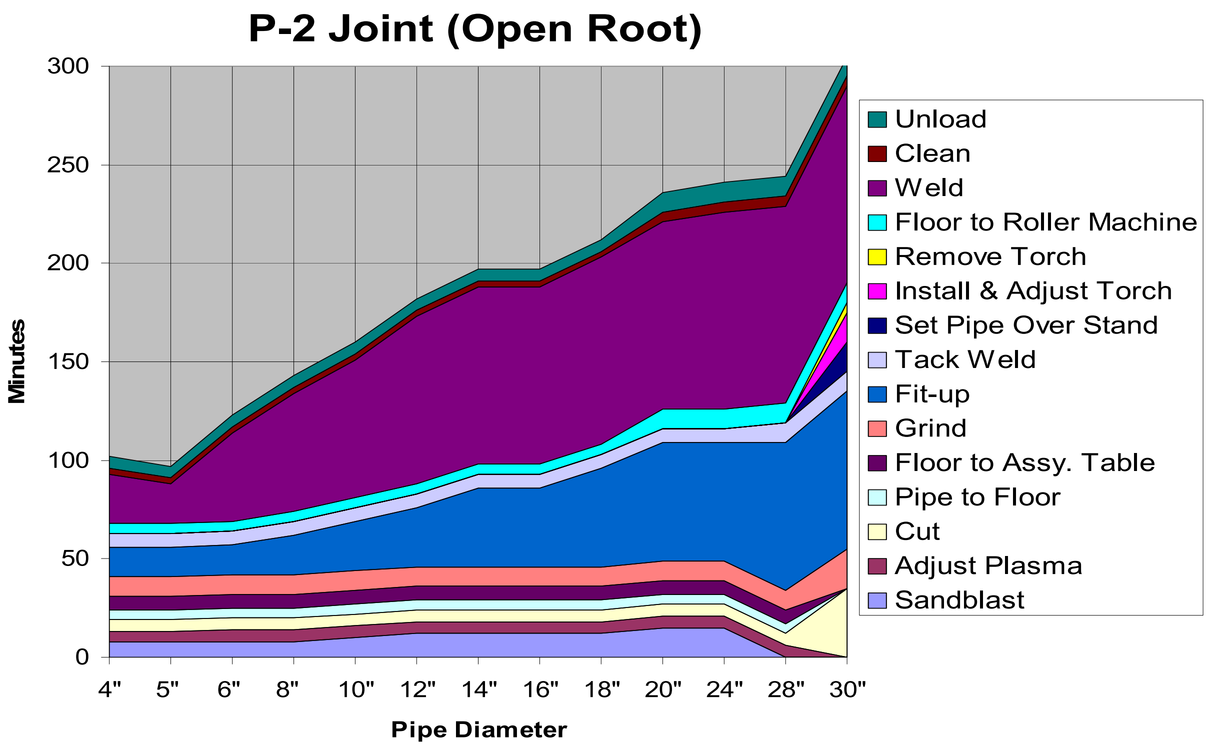

Figure **4**. Plot of process times for entire pipe joining process for P-2 "Open Root" joint .

Based on this, successful implementation of a single-pass, deep-penetration hybrid weld can be expected to result in dramatic savings in time and money, as well as a reduction in weld wire consumption, hazardous gaseous process emissions, and total heat input (for decreased distortion). Additionally, reducing the number of weld starts and stops results in fewer opportunities for defects and unproductive arc-off time. Comparing the fusion zones of hybrid and conventional welds, shown in Figure **5**, emphasizes these savings.

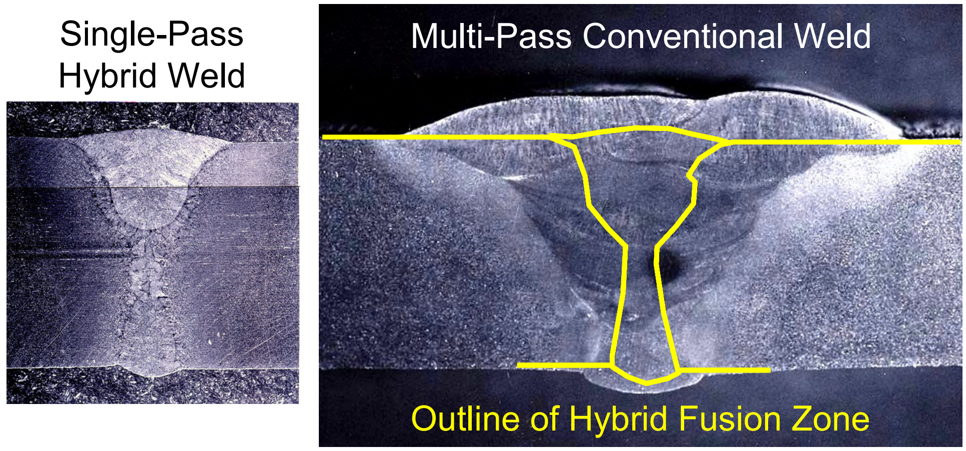

Figure **5**. Macrosections comparing fusion zone of single-pass hybrid weld of 0.5 inch thick plate to a multipass conventional weld.

This preliminary study indicated that the money saved by switching to a hybrid welding process would pay for the cost of a hybrid pipe welding system in two years [5]. These potential benefits provide strong justification for developing a joint design and hybrid weld parameter selection strategy that are straightforward and that result in a robust manufacturing process. They also justify the specification and implementation of a hybrid pipe welding system that can produce these single-pass welds for a wide range of pipe spool geometries. The program that was designed to realize these benefits is described in the next section.

PROGRAM DESCRIPTION

Proposed Project Plan

The initial objective of the program was to design, procure, and build a demonstration system for laser/GMA hybrid welding for pipe welding, then to perform a three month "pre-production" demonstration at NASSCO shipyard. This system was anticipated to generate significant savings through elimination of the multi-pass FCAW, GMAW, or GTAW of conventional beveled joints. With appropriate joint configuration and preparation, deep keyhole penetration provided by the laser and additional filler metal and heat input provided by the GMAW torch had previously been demonstrated to permit single-pass butt-welding of pipes [4].

The proposed system was to integrate the latest off-the-shelf technology to realize production hybrid welding in the ship building industry for the assembly of piping systems. A critical part of the effort was to address tight-tolerance pipe joint preparation, necessary to achieve a reasonable ROI, by identifying or developing a suitable edge preparation tool. The hybrid laser welding system itself was to employ a high-speed laser seam tracking sensor for following the joint, torch head manipulation, adjustment of weld schedule in response to gap fluctuations, and post-weld inspection. The system was to employ suitable clamping system or tack welding, and a pipe manipulation/rotation system to closely control travel velocity as required. The system was to include a laser/GMAW hybrid welding head completely integrated with the wire feeder and power supply. A suitable commercial system integrator was to be identified early in the project to participate in design reviews, and serve as the commercial outlet for the technology. These components were to be installed on a "portable" 40 foot transportation platform, so it could be easily shipped to other facilities for additional demonstrations.

The initial plan was to utilize ARL Penn State's 4.5 kW Nd:YAG laser system during system development and debugging. For the "pre-production" demonstration, it was assumed that another laser system would be utilized, through a leasing arrangement or other means.

The project was broken into three phases, with Go-No Go Decision Points between each phase. Phase I was to develop a design for a complete hybrid laser/GMAW pipe welding system (including edge preparation and fixturing), to select a system integrator, and to assemble an

industrial team to participate in design reviews. Phase II was to procure, assemble, and demonstrate the system at ARL Penn State using ARL's 6 kW Nd:YAG laser system. Phase III was to orchestrate the three month "pre-production" demonstration at NASSCO shipyard with actual NASSCO pipe welding personnel. An activity occurring in parallel with all these phases was to address qualification of the hybrid welding technique for this application.

Plan Execution

Over the course of the project, it became clear that improvements could be made to the plan that would help with the overall goal of demonstrating and implementing cost-saving hybrid pipe welding technology in the U.S. shipbuilding industry. Other modifications were precipitated by changing circumstances or events beyond the control of the lead investigators. The changes to the plan are outlined below.

From the start, it was recognized that the best means of developing an extended demonstration at a shipyard would be to lease a laser. Coincident with this, a new high power laser technology, i.e. fiber laser, was just entering the U.S. market. This laser technology is less expensive, offers a smaller footprint, is more energy efficient, and is robust and portable compared to conventional Nd:YAG high power laser technology. Additionally, the improved beam quality enables a smaller spot size which can be utilized for deeper penetration welding. Negotiations with IPG Photonics for the 7 kW fiber laser was initiated soon after the budget issues were resolved. A one year lease was required in order to integrate the laser into the hybrid pipe welding system and perform parameter development with the new laser prior to delivery to NASSCO. The initial quote was received March 2005 and the requisition was submitted in July 2005. Negotiations took an extended period of time, so the lease was not finalized until March 2006, and delivery of the laser to ARL Penn State occurred in June 2006. The laser lease was later extended an additional five months to allow for extended evaluations by NASSCO and a large multi-shipyard technology transition event and demonstration coordinated with an NSRP SP-7 Welding Committee meeting.

Planning and designing for the hybrid pipe welding system was initiated at the beginning of the project, with the intent of performing all design and construction activities at ARL Penn State. It became evident, though, that the Navy and U.S. shipbuilding industry would be best served if

ARL drew from resident experience and strength in laser processing and knowledge of shipbuilding to develop detailed specifications for the system, but then relied upon a commercial system integrator to complete the detailed design work and to build the system. This ensures the best value for detailed design and construction of the system through a competitive bidding process, the involvement of a for-profit entity enables adequate after-sale support, and this approach also provides U.S. industry with an experienced commercial supplier for future sales. In fact, a side benefit that was not anticipated is that the selected system integrator sold a similar hybrid laser-arc system to a major U.S. heavy equipment supplier based in part on our efforts in developing the hybrid pipe welding system. Regardless, the time in preparing and executing the competitive bid, as well as the time to negotiate the final contract, was underestimated.

Though the detailed specifications were completed by ARL Penn State in August 2005 and distributed to system integrators in September 2005, the initial proposals, received by November 2005, were thoroughly reviewed and determined to be inadequate. The Request for Proposal was revised and a request for Best-And-Final-Offers was distributed in January 2006. The revised proposals were received and reviewed, the bid from Wolf Robotics was selected. Negotiations began in March 2006, and the contract was awarded in May 2006. Though delivery of the completed hybrid pipe welding system to ARL Penn State was planned for September 2006, the complexity of the requirements resulted in a delayed delivery of a partially incomplete system in November 2006. Wolf Robotics sent engineers to ARL Penn State throughout December to complete the system. As a result of the delays, ARL Penn State had dramatically reduced time for parameter development on the completed system.

In February 2007, ARL Penn State conducted weeklong training for NASSCO welders and weld supervisors. In conjunction with this, ABS qualification activities for the first pipe size was conducted. This was followed by a system demonstration with open invitation to U.S. shipyard personnel. The system was shipped to NASSCO and commissioned in March 2007 for demonstration through June 2007. It was soon realized that parameter development and qualification for a broader range of pipe sizes was required to enable enough NASSCO production fittings to be processed to generate an adequate evaluation. The difficulty in obtaining suitable production fittings was exacerbated by the NASSCO management decision in

late 2006 to outsource much of the pipe joining operations to its sister organization in Mexico. Through mutual agreement, the shipyard demonstration was extended through September 2007.

In the time at NASSCO, more than 500 hybrid pipe welds were made in both steel and copper nickel allows, with pipe and fittings ranging from 4 to 30 inch diameter and up to 12.7 mm (0.5 inch) wall thickness. Additionally, 15 production pipe spools were completed. Details are provided later in the report.

SYSTEM DEVELOPMENT

For others engaging in similar activities, it may be instructive to review the initial system specifications, and compare it to the system that was finally delivered. The complete system specifications are included in Appendix A, but an abridged portion of the document is included here to illustrate the overall design strategy.

Initial Workcell Specifications

The request for bid required that the vendors provide a hybrid pipe welding system package that included several options. The workcell components to be integrated were broken out into a base system and two options. A Laser with Chiller was an assumed component of the system, and therefore was not listed. The Base Laser-GMA Hybrid Pipe Welding Workcell was to consist of the following major components:

a. Integrated Joint Tracking System
b. Weld Head Manipulation System
c. Rotary Positioner
d. Workcell Pendant
e. Workcell Control System / Programming Station (with safety system in accordance with ANSI Z-36)
f. Base / Support Structure
g. Safety Enclosure (with safety interlocks in accordance with ANSI Z-36, with suitable exhaust collection and filtration, and with process viewing via safety windows and/or video systems)

The vendors were also requested to provide quotes for the following two options:

Option A. In addition to the base system, supply:

h. HLAW Head
i. GMAW Power Supply And Wire Feeder

If Option A were not executed, a suitable HLAW Head and GMAW Power Supply and Wire Feeder were to be mutually agreed upon and integrated into the system, but they would be purchased by ARL Penn State.

Option B. In addition to the base system, supply:

j. Workcell Safety Enclosure (with signage and safety interlocks in accordance with ANSI Z-36, with suitable exhaust collection and filtration, and with process viewing via safety windows and/or video systems)

Note that a parallel effort was slated to provide a temporary safety shelter at NASSCO. If the WorkCell Safety Enclosure was not executed as an option, the shelter could alternatively be outfitted with suitable safety accessories.

Each major component is discussed in detail in the actual system specification documents in Appendix A. All vendors were requested to utilize commercially-available off-the-shelf (COTS) technology wherever possible.

One potential configuration for the workcell as envisioned by ARL Penn State was provided, and is shown in Figure 6.

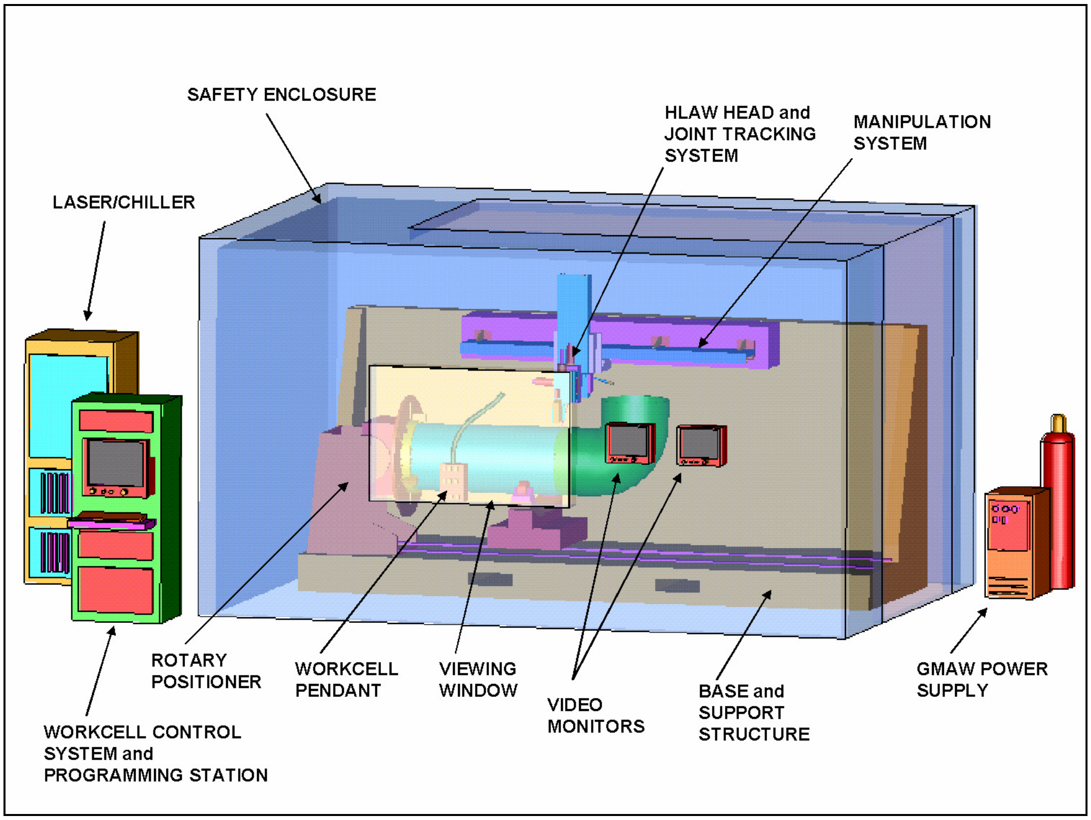

Figure **6**. Potential workcell configuration (for illustrative purposes only).

Process Flow

The desired high level process flow as seen from the perspective of the operator was provided to the vendors and is illustrated in Figure 7.

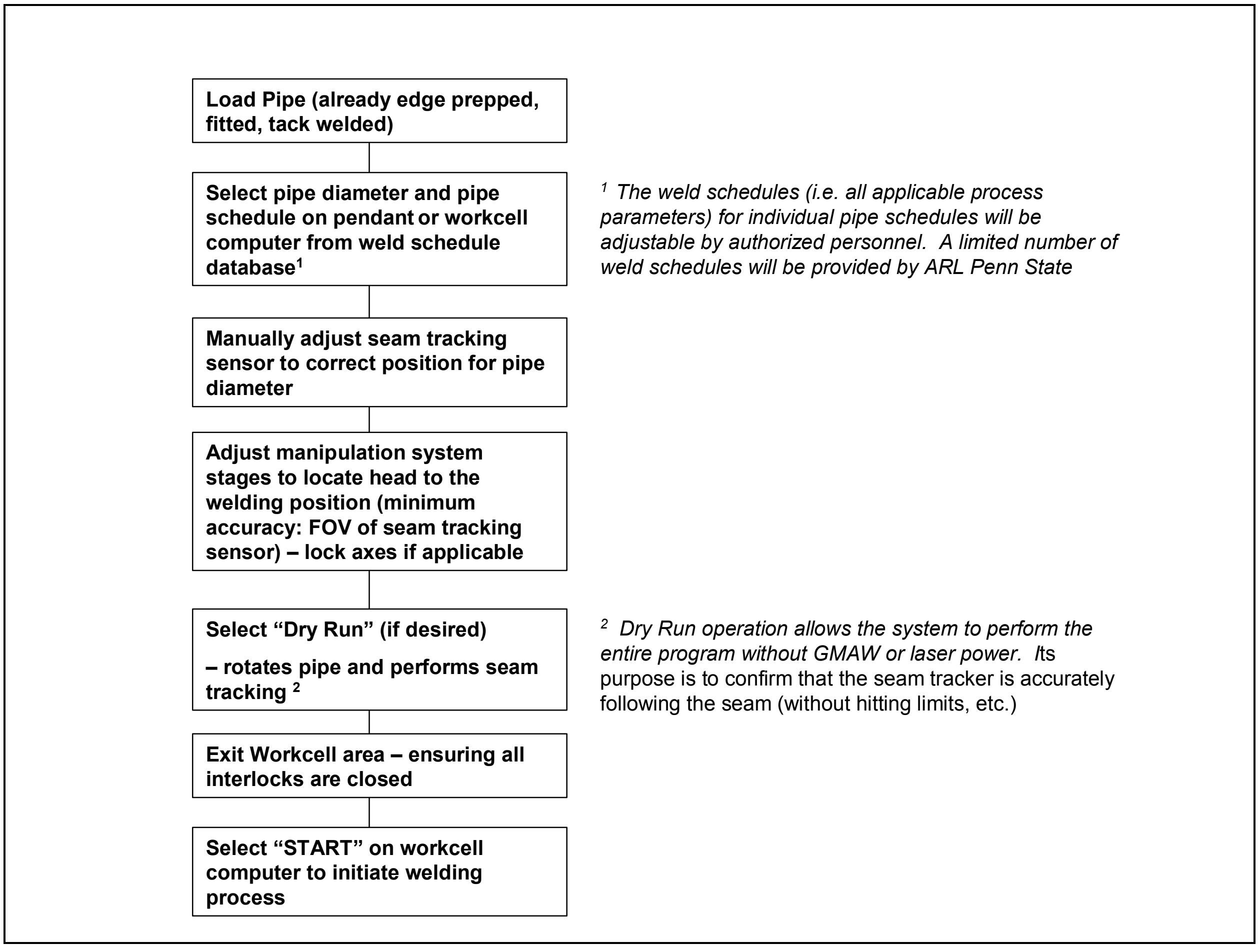

Figure **7**. High Level Operational Flow Chart[1]

Note that it was assumed that pipe edges could be prepared to edge quality sufficient for HLAW using commercial off-the-shelf joint edge preparation equipment to enable NASSCO personnel to fit-up and tack weld the joint. Discussions with pipe edge preparation equipment manufacturers indicated that this was possible.

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[1] Note that system was to be able to operate both with and without the Joint Tracking System activated.

Note that in the final demonstration system, it was envisioned that the operator would only be required to select the pipe diameter and schedule, but the software would also permit authorized personnel to add/edit/delete records from the weld schedule database (password protected).

The flow chart in Figure 8 was provided to illustrate the detailed process flow that was to be automatically executed by the Workcell Control System once the operator hit the "START" button. It also discusses the various parameters that were to be "programmed" into the weld schedule database for each pipe diameter and schedule.

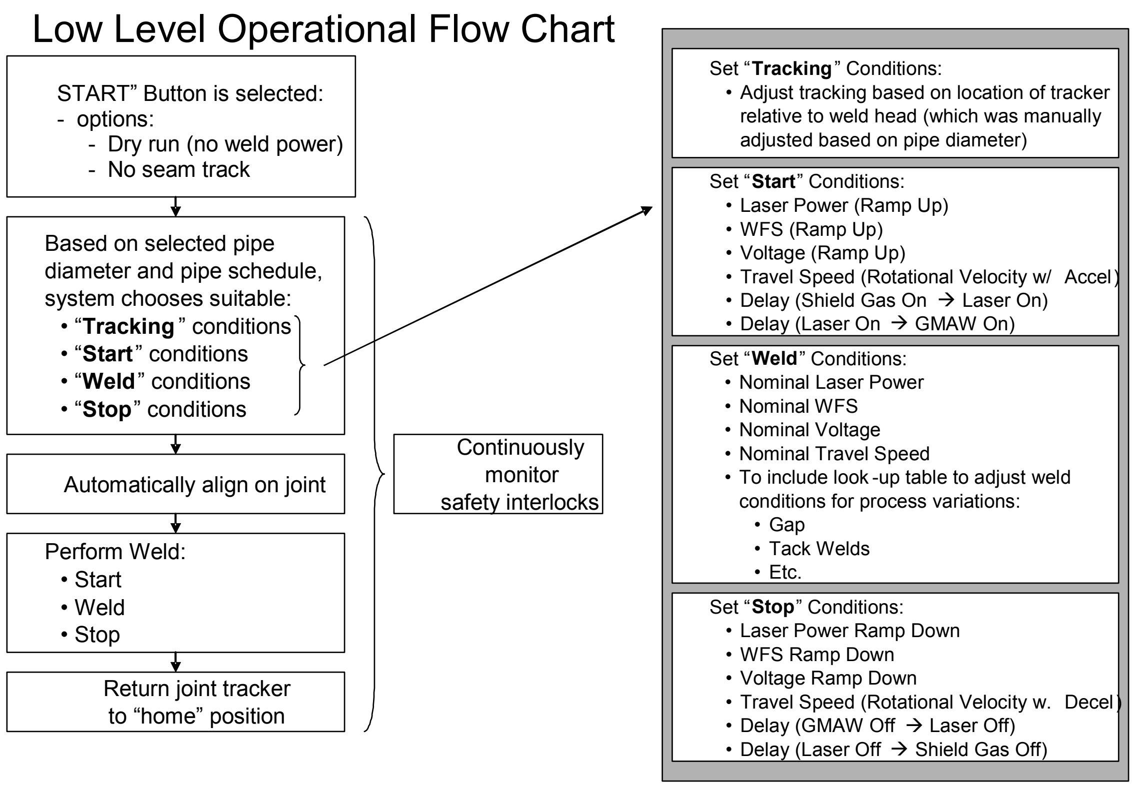

Figure **8**. Low Level Workcell Operational Flow Chart.

Since many GMAW power supplies offer on-board programming of start and stop conditions to prevent stub-in, burnback, crater fill, etc., it was deemed acceptable to rely on these rather than including them in the weld schedule database and control directly by the Workcell Control System, provided they produce acceptable welds in conjunction with the laser.

Work Cell Controls and Accessories

A list of controls and indicators that had to be made available to the operator from within the workcell are listed below in Figure **9**.

Manual Controls (pendant)

- GMAW
  - Wire Jog
  - Shield Gas Purge
- Laser
  - Aiming Laser On/Off
- Joint Tracking System
  - Jog +/- Y-axis
  - Jog +/- Z-Axis
- Weld Head Manipulation System (if powered)
  - Jog Up/Down
  - Jog +/- Along Length of Pipe (<15 sec)
  - Go to "Park" Position (<10 sec)
- Rotary Positioner
  - Jog CW/CCW
  - Jog Speed Adjustment
- General
  - E-Stop (halt entire process)

Indicators (pendant)

- Safety Interlock Tripped / Ready to Go
- Shield Gas On
- Laser Power On
- GMAW Power On

Figure **9**. List of Controls and Indicators to be provided to the operator on the Workcell Pendant.

The system specification was designed to address numerous practical considerations of welding with this new hybrid laser-GMA welding technology in a pipe shop. Critical items that were addressed in the specification include an ability to roll pipe assemblies, that can generate large moments as elbows are rotated, while maintaining a tightly controlled rotational velocity in order to maintain weld travel speed, ability to track the joint with high resolution to ensure the laser keyhole fully envelops the joint, ability to specify the laser power ramping and weld tie-in characteristics, ability to specify and store all process parameters for each weld, simple user interface and operation, and others. Please see Appendix A for additional details.

Selection Methodology

These Laser/GMA Hybrid Welding System specifications were distributed to numerous potential system integrators in a Request for Bid. In order to ensure a fair evaluation of the proposals, a Source Selection Organization was created to select the vendor whose proposal offered the best value to ARL Penn State and the Navy. The Source Recommendation Evaluation Board (SREB) consisted of a Source Selection Authority (SSA), a Technical Evaluation Panel (TEP), a Price Evaluation Panel (PEP), a Technical Advisor to the PEP, and a Legal Advisor.

A Source Selection Plan for the Laser/GMA Hybrid Welding System was executed on 9 September 2005. A copy of the non-weighted plan was provided to all members of the source selection organization for their use in evaluating proposals. The weighted plan was only provided to the SREB Chairman and the SSA.

On 12 September 2005, ARL Penn State issued a request for proposal to seven companies; four companies responded with proposals on 24 October 2005. It was determined that two of the companies were outside of the competitive range and were notified in writing.

Discussions were held with the remaining two companies in January 2006. At the conclusion of the discussions, ARL Penn State issued a request for revised final technical and price proposals, advising the two companies to provide recommendations for cost savings and to price cost savings as separate options. ARL Penn State received the two final proposals 03 February 2006.

The proposals were evaluated in accordance with the Source Selection Plan; each TEP member recorded their evaluation on the technical/management proposal numerical evaluation form. The TEP leader summarized the evaluation forms by calculating the average technical score for each evaluation factor and forwarded the completed summary form to the SREB Chairman. Technical and Management Factors were graded numerically and assigned weights as set forth in the Source Selection Plan. The technical/management proposals were evaluated according to Technical Approach and Technical Risk. Subfactors of Technical Approach listed in decreasing order of relative importance are: Soundness of Technical Approach; Robustness of Proposed Solution; Compliance with Technical and Deliverable Requirements; and Understanding of Technical Requirements. Subfactors of Technical Risk listed in decreasing order of relative importance are: Experience in Designing and Building Similar Systems; Qualification of

Technical and Management Personnel Assigned to the Program, and Demonstration of Understanding of Technology Necessary to Design and Build the Proposed System are of equal importance; Quality of Fabrication Facilities; and Quality of Testing Facilities and Equipment.

The PEP evaluated the pricing proposals for price realism and responsiveness to the solicitation in accordance with the Source Selection Plan. The Pricing Proposal Evaluation forms were forwarded to the SREB Chairman.

The SREB Chairman completed the Overall Evaluation Summary Form, by applying the evaluation factor weights to the average technical score for each evaluation factor. The conclusion from the Overall Evaluation Summary Form indicated that the Wolf Robotics' proposal provided the best value to ARL Penn State and the Navy based on the proposed price/total weighted score calculation.

Final System

Wolf Robotics proposal was selected and the firm then designed and integrated the Hybrid Pipe Welding System. Frequent communication between ARL Penn State and Wolf Robotics, coupled with a strong spirit of teamwork, helped to ensure that the system design met the objectives as the design details solidified over time. In particular, the operator interface went through numerous iterations to ensure that it provided a useable and powerful interface to all the components of the system. The final system is shown installed at GD NASSCO in Figure 10 through Figure 12. The figures include a bird's eye view of the system installed in the pipe shop; the operator area and pipe preparation and staging area are on the left side, the robot welding area is on the top-right, and additional storage is on the bottom-right. Note that the ceiling was intentionally left off and entryways do not have headers so that the overhead crane has access to accommodate positioning of large pipe spools.

Figure **10**. Photograph of the outside of the hybrid pipe welding system enclosure at NASSCO shipyard pipe shop.

Figure **11**. Several views of the hybrid pipe welding system installed at NASSCO shipyard.

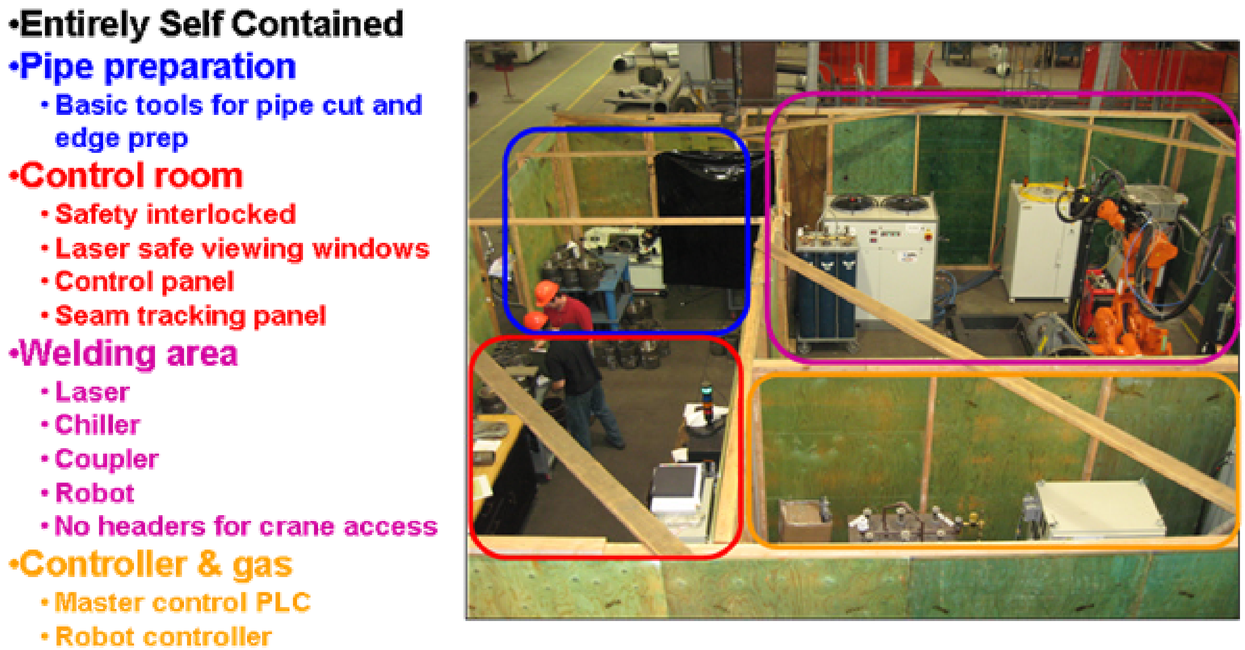

Figure **12**. Bird's eye view of the hybrid pipe welding system installed in NASSCO's pipe shop.

The final integrated system includes a 7 kW IPG Photonics fiber laser (YLR-7000), a Fronius pulsed synergic GMAW power supply (Transpulse Synergic 50000MV 500A supply with integrated FK 4000 cooling unit), an ABB 6-axis articulated arm robot (IRB 4400 with M2000 robot controller) coupled to a large rotary positioner serving as the 7th robot axis, a ServoRobot seam tracking system (Rafal-SSO 3-d laser vision camera coupled with a Pilot-LW control box linked to both y- and z-axis linear stages with 30mm stroke), and the customized Wolf Cell Controller, to provide an easy-to-use operator interface and communications and control of all system components.

The typical procedure for using the hybrid pipe welding system to join a pipe spool (typically welding pipe to a fitting) is outlined below:

1. Load
   - Remove the previous pipe from the rotary positioner
   - Load the current pipe onto the rotary positioner
   - Check cover glass, clean if necessary
2. Teach Joint
   - Input set-up data at the Wolf Cell Controller, including the serial number

- Teach weld starting point
- Finish set-up

3. Weld
   - Weld the pipe
   - Inspect the weld

In each case, after the pipe is loaded into the rotary positioner (overhead crane access is provided for large pipe spools), the operator selects the weld diameter and schedule from the touch-screen user interface, and the pre-determined welding parameters are loaded into the welding program. Some of the screens used for these operations are shown in Figure 13. The operator must then jog the robot head close enough to the joint for the seam tracking system to register the joint with the joint tracking system, to serve as the weld starting point (a close-up image of the operator teaching a test joint is shown in Figure 14). Robot safety and laser safety are important considerations, and the system is designed to offer redundant interlocks and user controls to address these concerns. When the operator is safely outside the welding area, the weld can proceed and the operator can watch through a laser-safe window covered with a conventional arc welding curtain. After the robot completes the weld, it moves safely back to a so-called PARK position to enable a crane to off-load the welded spool.

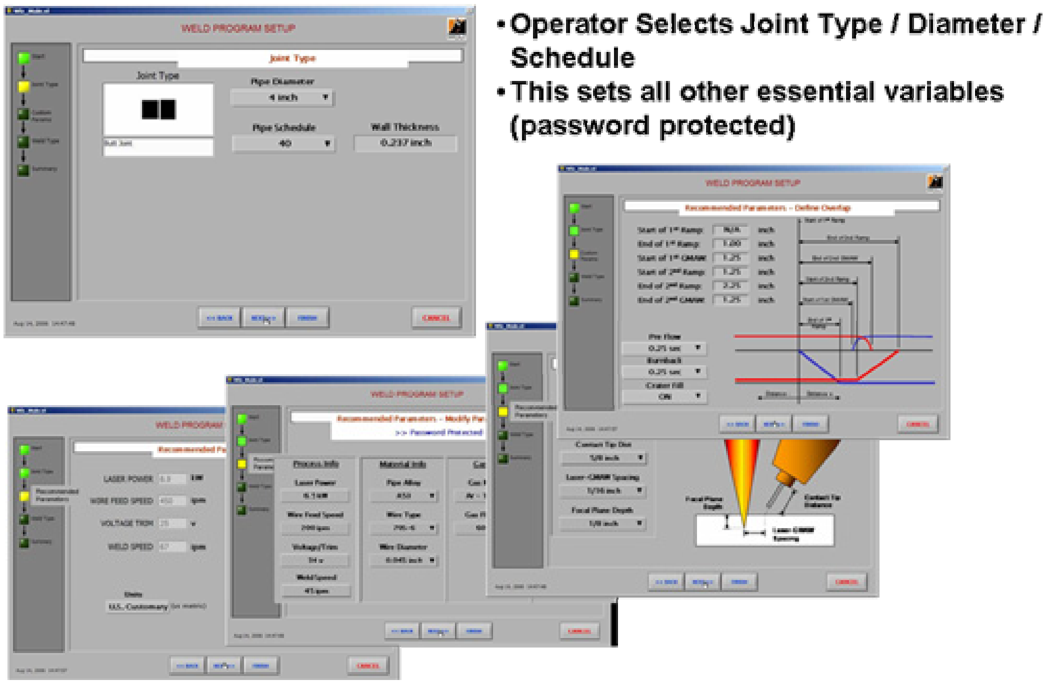

Figure **13**. Examples of Operator Interface Screens.

Figure **14**. Photograph showing the operator jogging the robot to teach the approximate joint location.

Note that an especially important innovation that was developed is the ability to specify quite complex weld paths for joints that are angled and offset with respect to the rotational axis with the operator specification of a single point. In other words, if the operator selects the pipe diameter on the screen, then teaches a single point, the entire weld path is determined. This allows for a remarkable degree of flexibility for the system in processing a significant percentage of the various and sundry pipe spools that NASSCO must manufacture.

For training of NASSCO personnel at ARL Penn State prior to shipment of the system to NASSCO, ARL Penn State created a compilation of training documentation. Items included in the documentation include:

- System overview
- Installation logistics
- Safety
- Installation and Operation Manual provided by Wolf Robotics
- Overview of system components and software
- Overview of manual operations possible using the ABB robot teach pendant
- Miscellaneous reference documentation and troubleshooting information
- Miscellaneous set-up documentation and schematics

Though not all documentation is provided in this report, the section that provides an overview of the system components and software is included as Appendix B, as it may shed additional light on system operation to the interested reader.

HYBRID PROCESS DEVELOPMENT

Throughout the project, numerous experimental investigations were conducted to help develop a basic understanding of the effects of various parameter changes on hybrid weld quality. These parameters include joint geometry, laser power, voltage, wire feed speed, travel speed, laser-to-GMAW torch spacing, and others. Practical aspects of hybrid welding that are not typically addressed in academic studies were also investigated, such as welding over tack welds, start-stop overlap conditions, ramping of laser power, gap tolerance, vertical mismatch, etc. Finally, when the final complete system was commissioned with the IPG fiber laser, additional experiments were necessary to optimize parameters for the new processing conditions. The experimental studies are presented in three phases, corresponding to the actual progression of the work.

Phase I Experiments at ARL Penn State

Phase I Experimental Objective

A series of experiments were run to investigate the effects of varying joint design and process parameters. Specifically, the effects of changing bevel angle and land height on the size and shape of the fusion zone were investigated. Since much of the literature has examined autogenous laser weld penetration in flat plate, initial experiments examined penetration and fusion zone geometry in various beveled butt joints. The effects of travel speed and laser-to-GMAW torch spacing were then studied. One of the hybrid welded joints was subjected to mechanical testing and radiographic examination. Finally, practical aspects of hybrid welding, such as welding over tack welds, overlap of weld start and stop (required for circumferential pipe welds), and gap tolerance were investigated.

Phase I Experimental Plan

A variety of autogenous laser and laser-GMA hybrid welds were performed using a combination of a Trumpf diode-pumped 4.5 kW Nd:YAG laser and a Lincoln PowerWave 455 STT GMAW power supply (operated in constant voltage mode). The welds were performed on mild steel butt joints (A36) using 70S-6 filler wire at a diameter of 0.045 inch. In general, 4.5 kW of laser power was focused at the top surface of the plate of bottom of the bevel, and Ar-10% CO_2 shield gas was supplied through the GMAW torch head. When laser-to-GMAW torch separation was

large in enough to permit it, an additional gas nozzle directed N_2 gas at the laser keyhole for plasma suppression and supplemental shielding.

Experiments were performed on a variety of butt joint configurations to investigate potential effects of variations in bevel angle and land height (see Figure **15**). Initial experiments involved autogenous laser welds at various speeds to compare penetration in beveled joints to flat plate penetration data.

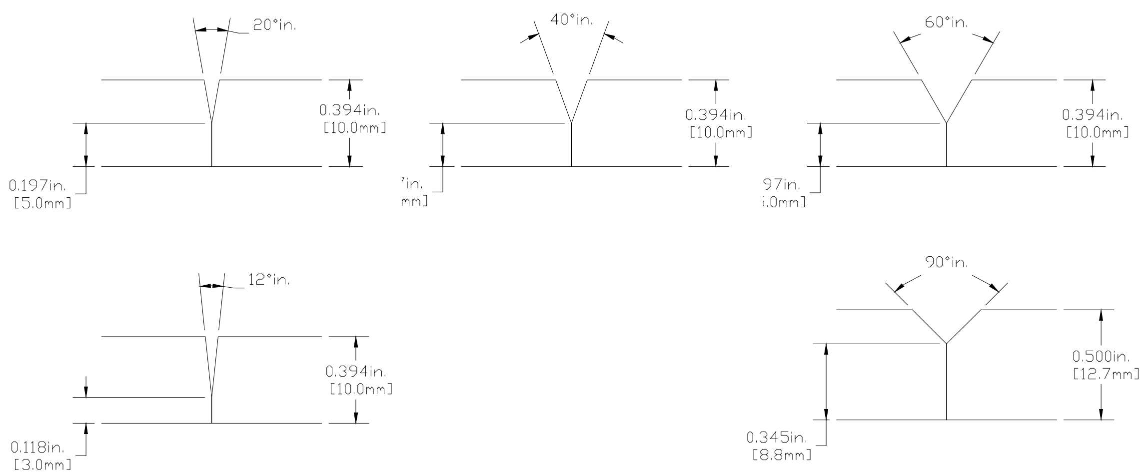

Figure **15**. Joint configurations employed in this work.

The laser and GMAW torch head were configured as shown in Figure **16**. In all experiments, the contact-tip-to-workpiece-distance (CTWD), measured from the bottom of the joint as shown, was held constant and the laser-to-GMAW torch spacing (4 mm in the figure) was varied[2] to observe the effects on process robustness, fusion zone geometry, and weld quality.

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[2] Note that "hybrid" welding can be defined in different ways. Throughout this report, "hybrid" is meant to refer to a laser beam weld and GMA weld taking place simultaneously in close proximity. It has been noted in the literature that "hybrid" often refers to laser beam and GMAW wire impinging on the part within 0–2 mm. In many of our experiments, the laser beam led the GMAW wire by 10 mm or more. It was suggested that "tandem welding" may be a better way to refer to welds that use this spacing. Though we have chosen not to use this terminology in this report, it is a noteworthy distinction.

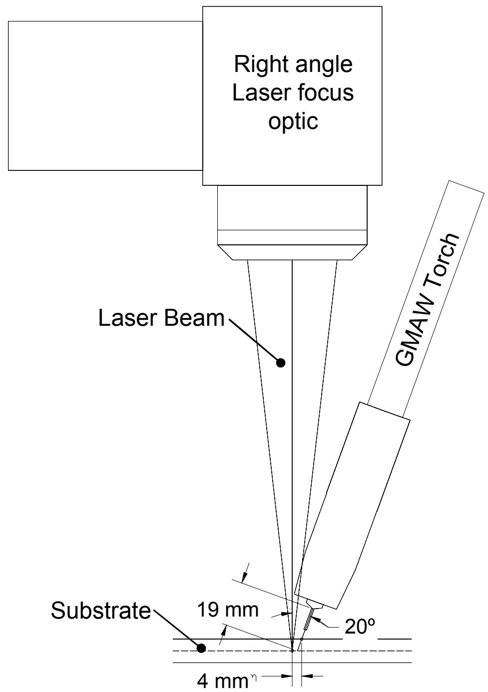


Figure **16**. Sketch shows the hybrid configuration and the definition of laser-to-GMAW torch spacing.

Phase I Experimental Results

Autogenous Laser Welds

In the first set of experiments, joint land height was constant, and the bevel angle was varied. Cross sections of these welds can be seen in Figure **17**. The information gathered was used to help guide the strategy for the hybrid experiments.

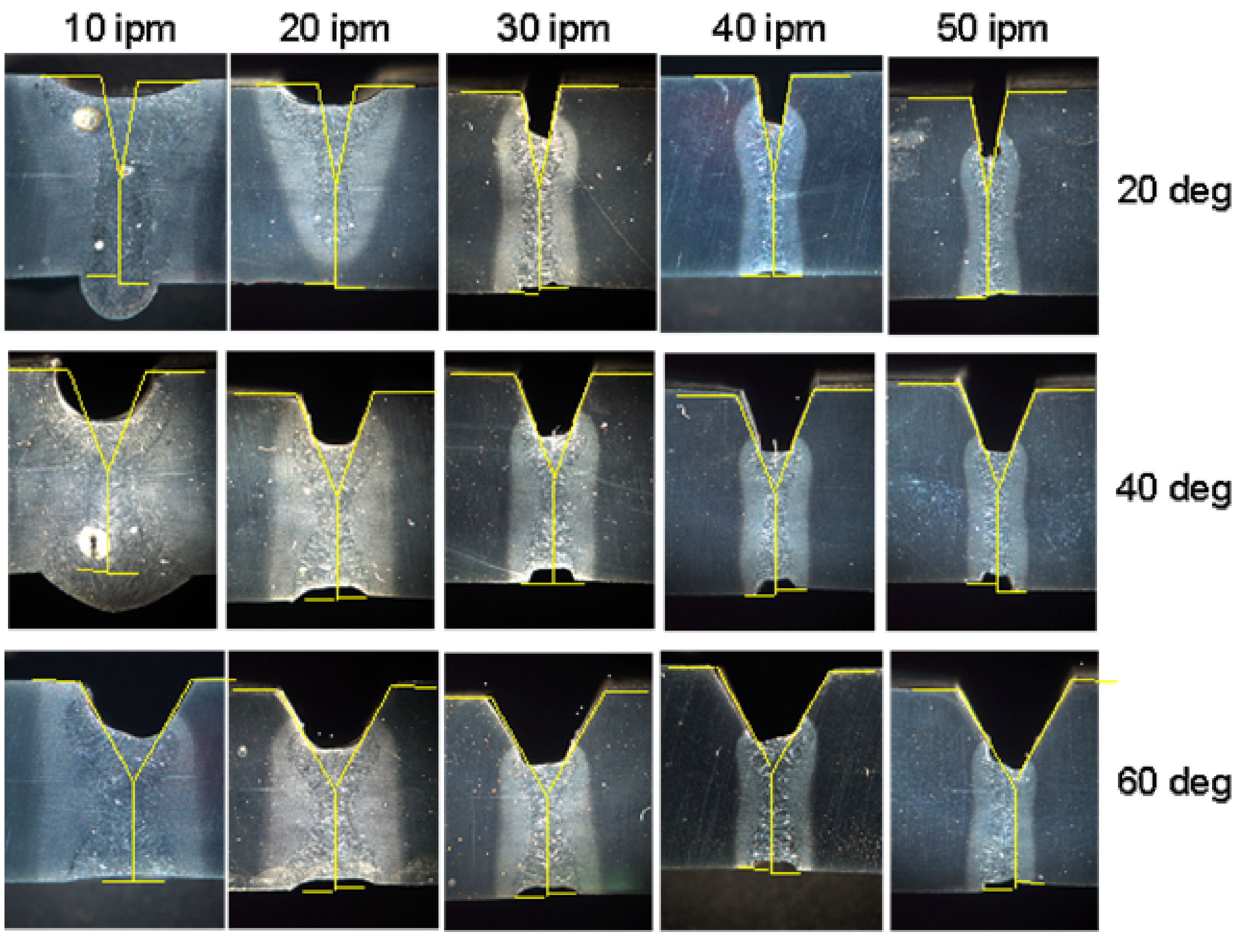


Figure **17**. Autogenous laser welds in different joint configurations (10 mm thick mild steel, 5 mm land).

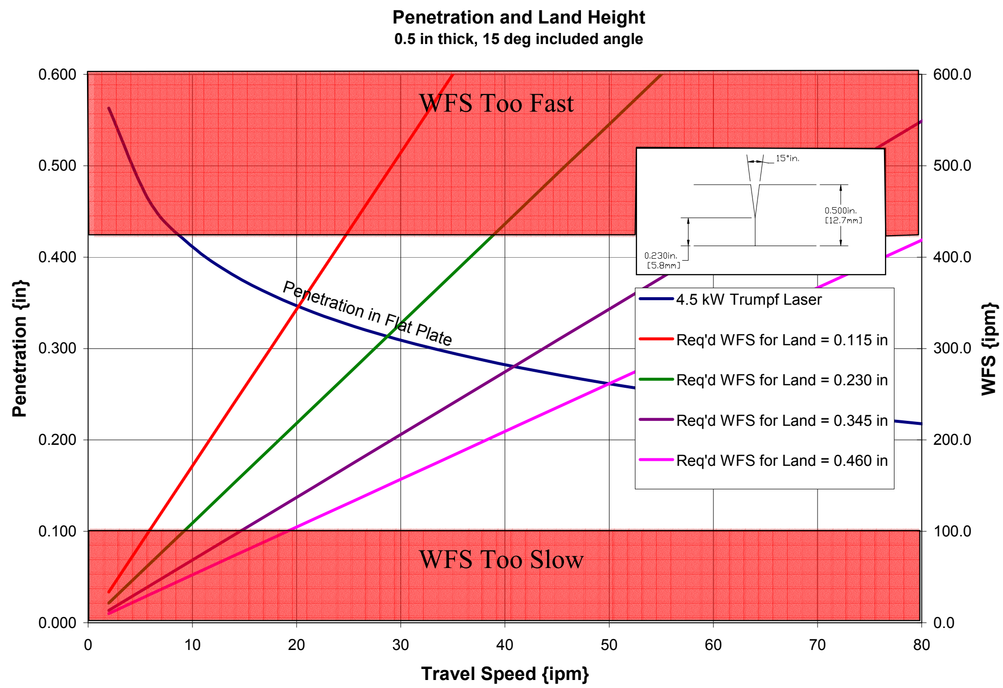
These data demonstrate that in the narrow angle joint (20º), travel speed of 10 ipm (~0.25 m/min) is slow enough to enable melting of the sides of the joint, and the large heat flux per unit length results in a highly viscous melt pool which drips and blows-through the bottom (an unacceptable condition as the backside weld bead geometry is quite inconsistent). At a slightly faster speed of 20 ipm, (~0.5 m/min), the laser is still slow enough to melt the joint sides, but the molten material from the sides serves to fill the joint with additional material and effectively increases the penetration depth required to result in a full penetration weld. As a result, full penetration is not achieved. As speed is increased further, the sides do not melt, so no material is available to fill the joint, and full penetration is again achieved, over a wide range of travel speeds.

Another interesting observation that can be made is that the larger angle joints and slower speeds seem to experience a greater degree of backside undercut. Apparently the molten material is being drawn-up into the joint due to surface tension effects. The evidence is not conclusive, but it seems logical that this effect is related to amount of joint cross section that is filled by the molten material, and the wetting angle the molten material makes with respect to the joint walls. At slower speeds, more of the joint is filled and the melt pool is hotter and less viscous, with the consequence that the undercut seems to be more pronounced.

Hybrid Laser-GMA Welds

Experimental Strategy

A large number of processing parameters are available when the LBW and GMAW processes are combined. The complexity is further increased when joint geometry is also varied. To simplify the task of choosing parameters and joint geometries, several assumptions were made. First, if the wire diameter is known, a simple geometric relationship can be used to determine the wire feed speed (WFS) required to fill a joint of a given geometry (i.e. a given thickness, land height, and included bevel angle). In general during these experiments, WFS was increased to provide an additional 5 mm^2 to the cross-sectional weld bead reinforcement. Since GMAW is only effective through a certain range of WFS (in this case, about 100–425 ipm), this serves to limit selection of joint geometry. For example, Figure **18** shows plots of the required WFS for both a 15º and 90º included bevel angle at various land heights. Note that for a 15º bevel angle and a land height of 0.230 inches, and with the known range of WFS for this power supply, travel speed can vary between 10–38 ipm, but if considering a 90º joint with same land height, weld speed is limited to 3–9 ipm in order to provide enough filler material to fill the joint.



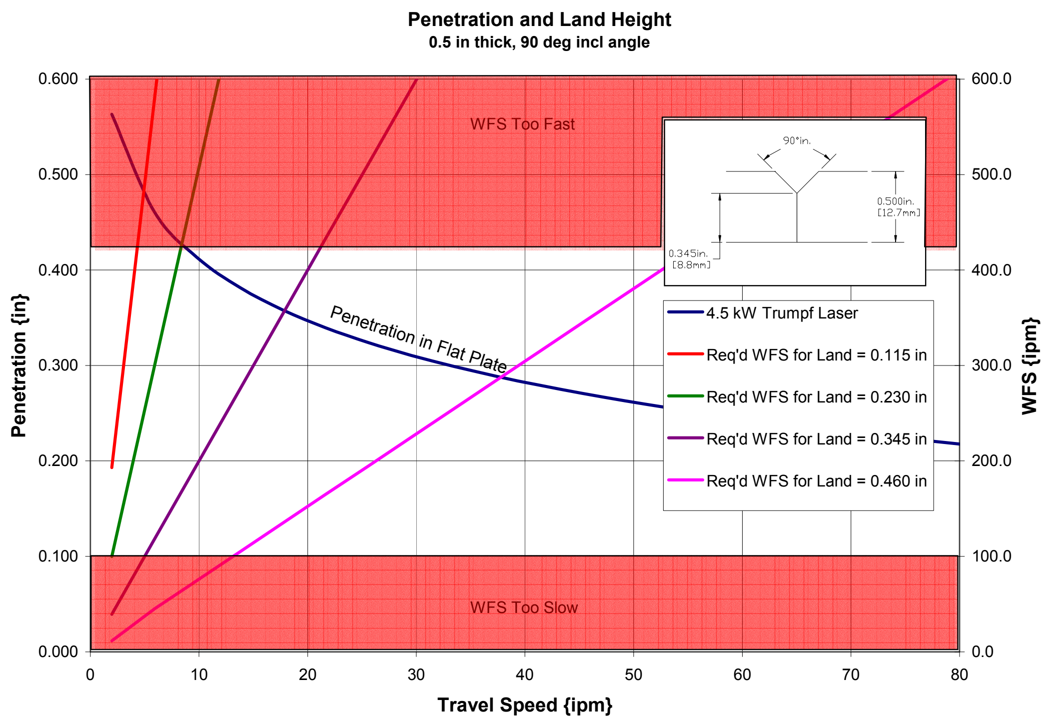


Figure **18**. Plots showing laser penetration and WFS required to fill joints at different angles and various land heights as a function of travel speed (laser penetration in flat plate also shown).

Laser to GMAW Torch Spacing

The first set of experiments investigated the effect of increasing spacing between the laser and the GMAW torch. Cross-sections of the welds are shown in Figure **19**. It has been widely reported that a synergistic effect occurs when the two processes are spaced near one another, however in this type of beveled butt joint additional observations can be made.

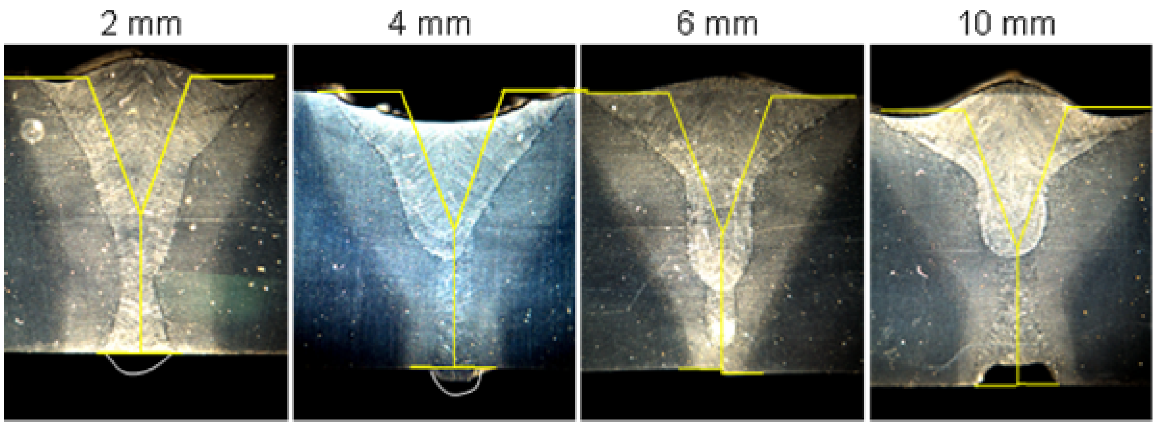


Figure **19**. Macroscopic cross-sections illustrate how increasing spacing changes the fusion zone profile (10 mm thick, 5 mm land, 40º included angle, 36 ipm travel speed, 350 ipm WFS).

For this set of processing parameters, at both 2 and 4 mm spacing, it appears that full penetration has been achieved and full mixing throughout the fusion zone has occurred. However, while not completely evident in the cross-sections, significant backside blow-through was present in both cases, resulting in unacceptable weld quality. At slightly more distant spacing, 6 mm, full penetration was not achieved and there appear to be two separate solidification events, as evidenced by the two distinct fusion zones. At still larger spacings, full penetration is again achieved. However, there are clearly two separate fusion zones, so mixing between the filler material and the laser keyhole melt pool does not occur. Additionally, the same backside undercut is observed as in the autogenous laser welds (refer to Figure **17**).

It is believed the reason for these observations is that at near spacing the laser beam must penetrate the base metal *as well as* the additional material provided by the filler wire (which tends to flow slightly ahead of the wire). In this case, the combined process provides enough heat to result in full penetration, albeit accompanied by backside blow-through. As the spacing

is increased to 10 mm, the melt puddle formed by the laser *leads* the GMAW puddle, so that no additional material is introduced to the joint in the region where the laser beam is striking the substrate. This is illustrated in Figure **20**.

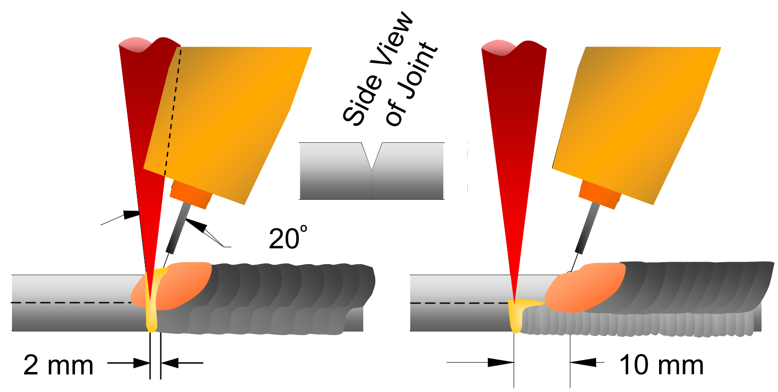


Figure **20**. Illustrates how close spacing may cause the laser beam to interact with the GMAW puddle, while increased spacing permits laser to directly irradiate the bottom of the joint.

At intermediate spacing, high speed videography reveals that the laser and GMAW-generated melt puddles experience some degree of mixing (see Figure **21**). Note that travel speed also affects the degree of puddle interaction. This is observed and discussed below.

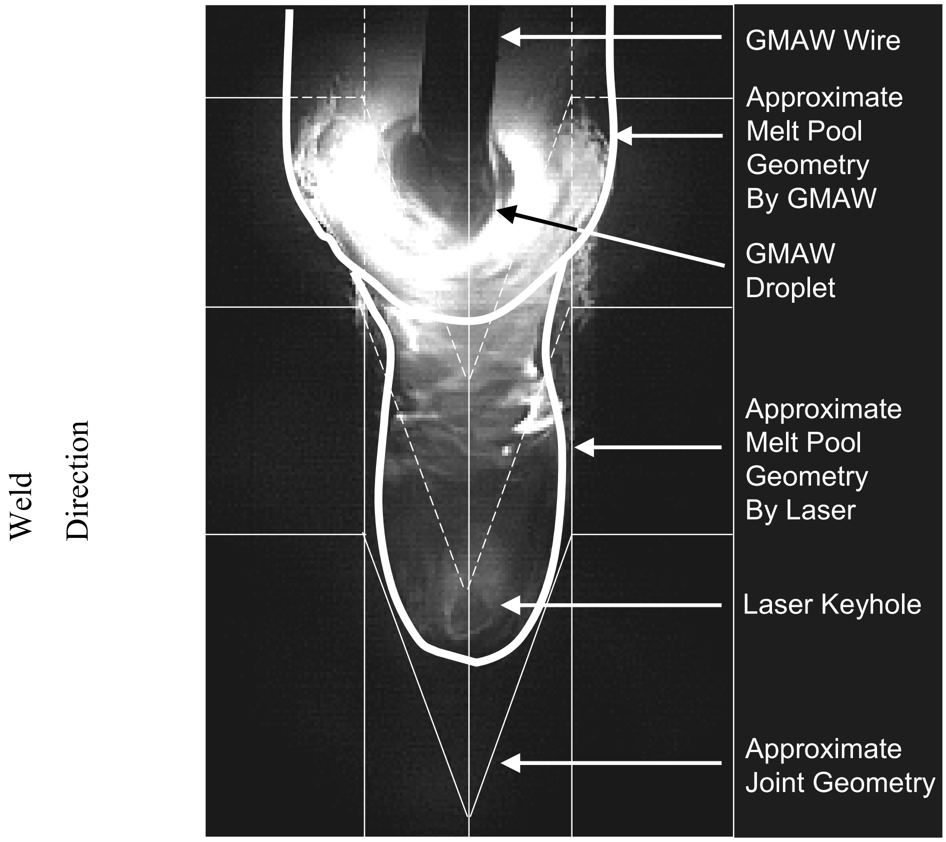


Figure **21**. High speed image of intermediate spaced hybrid weld (7 mm spacing, 10 mm thick, 5 mm land, 20º included angle, 20 ipm travel speed, 200 ipm WFS—weld is moving toward the viewer).

Spacing and Travel Speed Effects

In this set of experiments, both laser-to-GMAW torch spacing and travel speed were varied to observe the effect on fusion zone geometry. In this case, the land height and the joint angle are reduced (3 mm and 12º, respectively). The results are shown in Figure **22**.

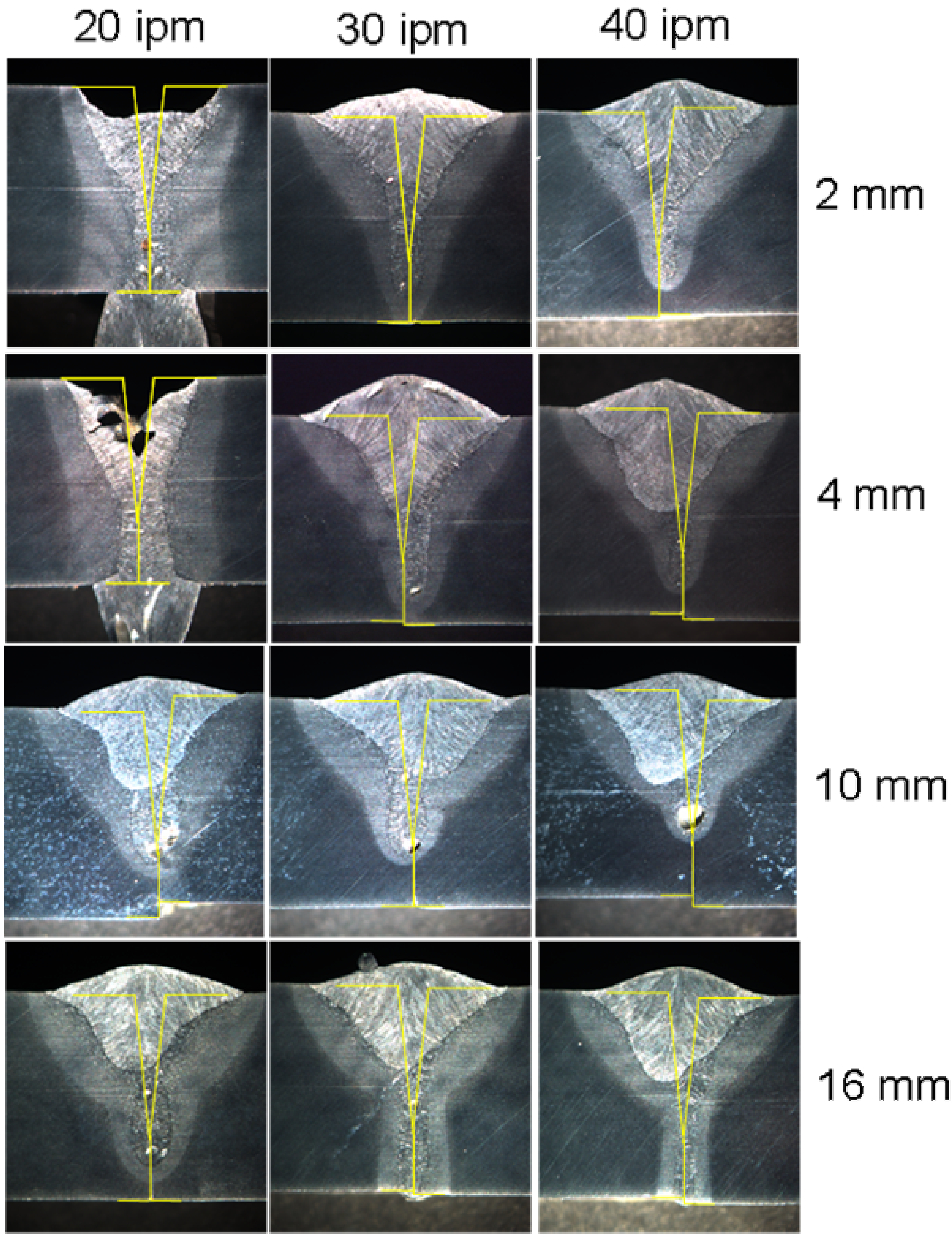


Figure **22**. Macroscopic cross-sections illustrate effects of laser-to-GMAW torch spacing and travel speed on fusion zone geometry (10 mm thick, 3 mm land, 12º included angle, 20, 30, 40 ipm travel speed, 200, 300, 350 ipm WFS).

At low travel speed (20 ipm) and near spacing, good mixing is again achieved, but the process is prone to backside blow-through (an unacceptable condition, as backside weld bead geometry is extremely inconsistent). At this travel speed, however, more distant spacing does not lead to full penetration. This seems to indicate that at low travel speed the laser beam interacts with the material introduced by the GMAW process, even at laser-to-GMAW torch spacing up to 16 mm.

As speed in increased with near spacing, the reduced heat flux per unit length prevents full penetration. However, as laser-to-GMAW torch spacing is further increased, complete penetration is observed to occur at much higher travel speeds. Additionally, the narrow joint angle has prevented undercut on the backside (as expected from observation of the autogenous laser welds of Figure **17**). This indicates that at higher speeds and distant laser-to-GMAW torch spacing, the laser beam does not interact with material introduced by the GMAW process.

Process Robustness with Near Laser-to-GMAW Torch Spacing

The previous experiments demonstrated that full penetration is achieved with near spacing and slow travel speed, but the process is then prone to backside blow-through. At constant spacing (either 2 or 4 mm), an increase in travel speed of 50% resulted in incomplete penetration. Figure **23** shows results of an experiment to determine whether or not an intermediate travel speed could successfully provide full penetration while preventing backside blow-through.

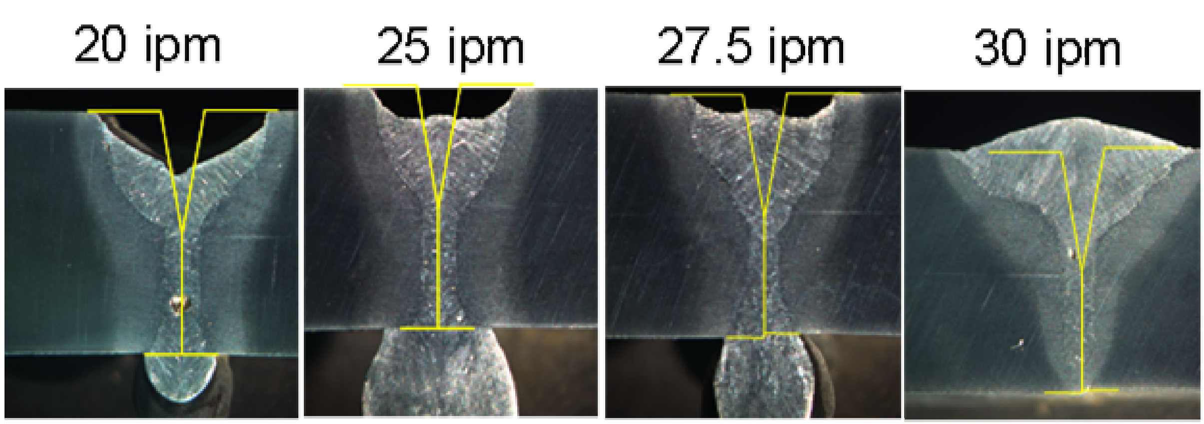


Figure **23**. Macroscopic sections illustrate that at close spacing, the process is intolerant to small changes in travel speed (10 mm thick, 5 mm land, 20º included angle, 2 mm spacing, 20, 25, 27.5, 30 ipm travel speed, 200, 250, 275, 300 ipm WFS).

The results indicate that hybrid welding at near spacing is intolerant to small variations in travel speed, i.e. a 10% change in travel speed dramatically alters whether or not backside blow-through or incomplete penetration occurs.

Process Investigation with Distant Laser-to-GMAW Torch Spacing

From the previous results, it is evident that near spacing can provide full penetration and complete mixing, but is prone to backside blow-through and is intolerant to process variation. An additional advantage to near spacing, and one often cited in the literature, is that the additional filler wire in the region of the laser keyhole can help compensate for welding issues that arise due to gap variation. Autogenous laser welding with gaps is notoriously prone to either (a) pass through the gap thus limiting melting, or (b) melt the substrate but with inadequate reinforcement. However, a larger separation allows for simpler process parameter development since the LBW and GMAW processes are not strongly coupled. Additionally, it seems to result in a more stable and robust process.

Although a narrow joint would theoretically enable complete fill with a single-pass GMAW process at high speeds, in practice welding of this type often results in incomplete fusion at the root (see top of Figure **24**). The additional heat provided by a laser beam, even when leading by up to 16 mm, seems to provide enough energy to enable complete fusion, with the added benefit of increased penetration of the land.

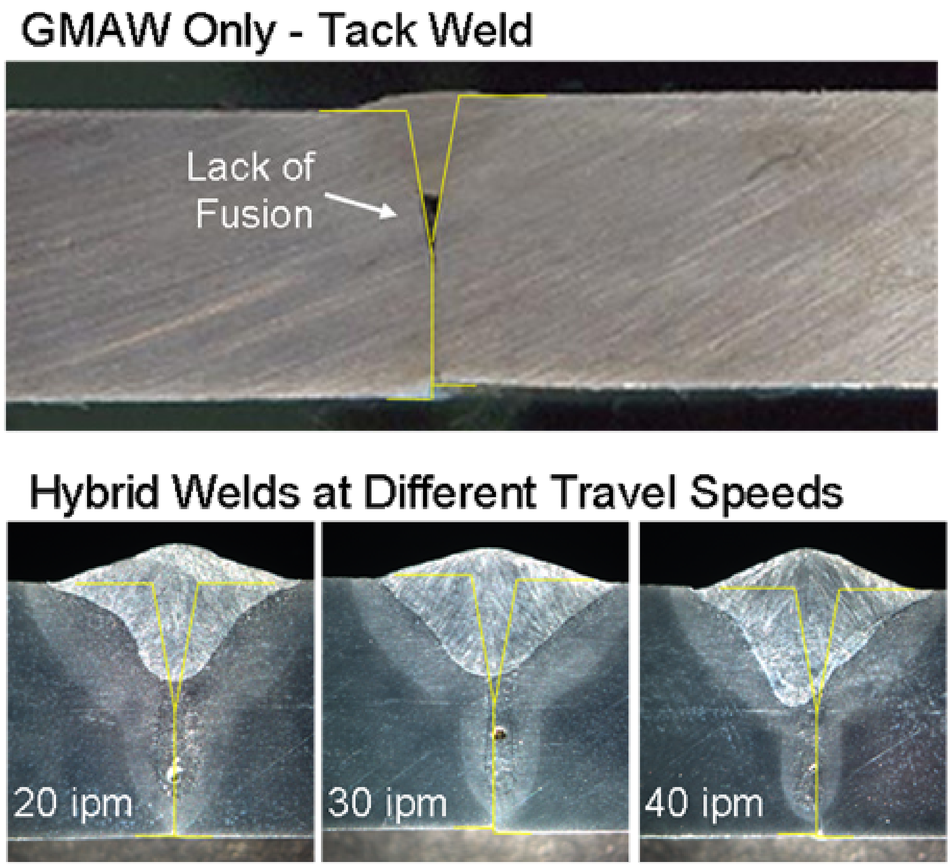


Figure **24**. Cross sections demonstrate how leading laser even at 16mm spacing seems to provide enough additional heat to assist in achieving complete fusion with the GMAW weld, even in narrow groove openings. (10 mm thick, 5 mm land, 20º included angle, tack weld at 40 ipm travel speed and 200 ipm WFS, hybrid welds at 20, 30, 40 ipm travel speed, 200, 300, 350 ipm WFS).

Testing of Hybrid Weld

Through experimentation, a set of hybrid welding processing conditions was found to join 12.7mm (0.5 inch) thick A36 steel with a visually acceptable weld. The weld produced full penetration, desirable reinforcement on the top and bottom surfaces, and demonstrated an ability to compensate for some degree of vertical mismatch (see Figure **25**).

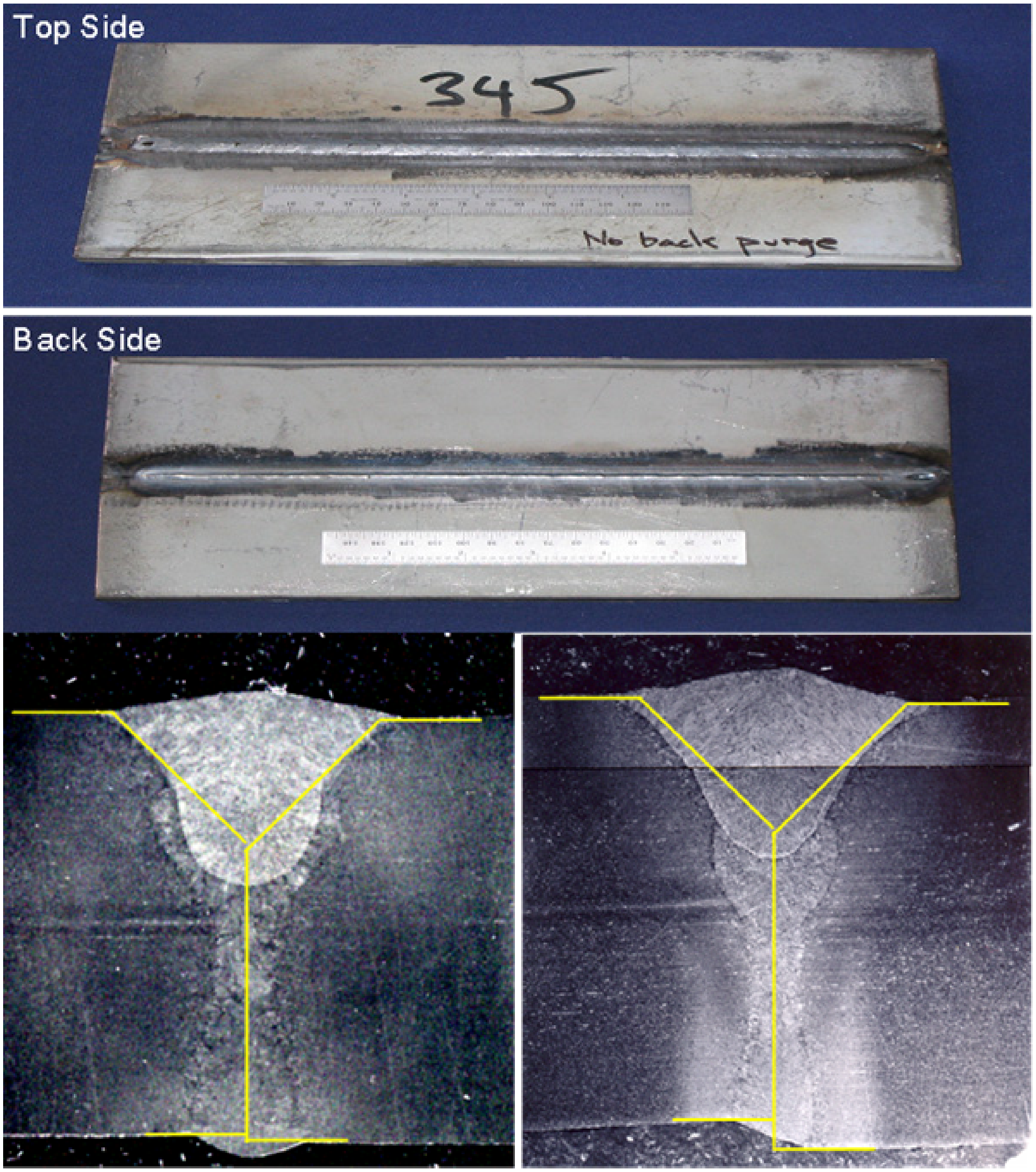


Figure **25**. Hybrid welds used for mechanical and radiographic testing —12.7 mm (0.5 inch) thick, 8.8 mm (0.345 inch) land, 90º included angle, 16 mm spacing, 10 ipm travel speed, 200 ipm WFS.

The welded joints were subjected to face and root bend tests and reduced section tensile tests (see Figure **26**). In all cases, the failures occurred outside the weld heat affected zone, indicating acceptable mechanical properties.

Figure **26**. Mechanical testing of hybrid weld in 0.5 inch thick mild steel indicated adequate mechanical properties.

The welds were also subjected to radiographic testing (see Figure **27**). Though the bulk of the weld is porosity free, these tests revealed a small degree of porosity near the beginning and end of the weld. More investigation is required to determine the cause of this porosity and to eliminate it.

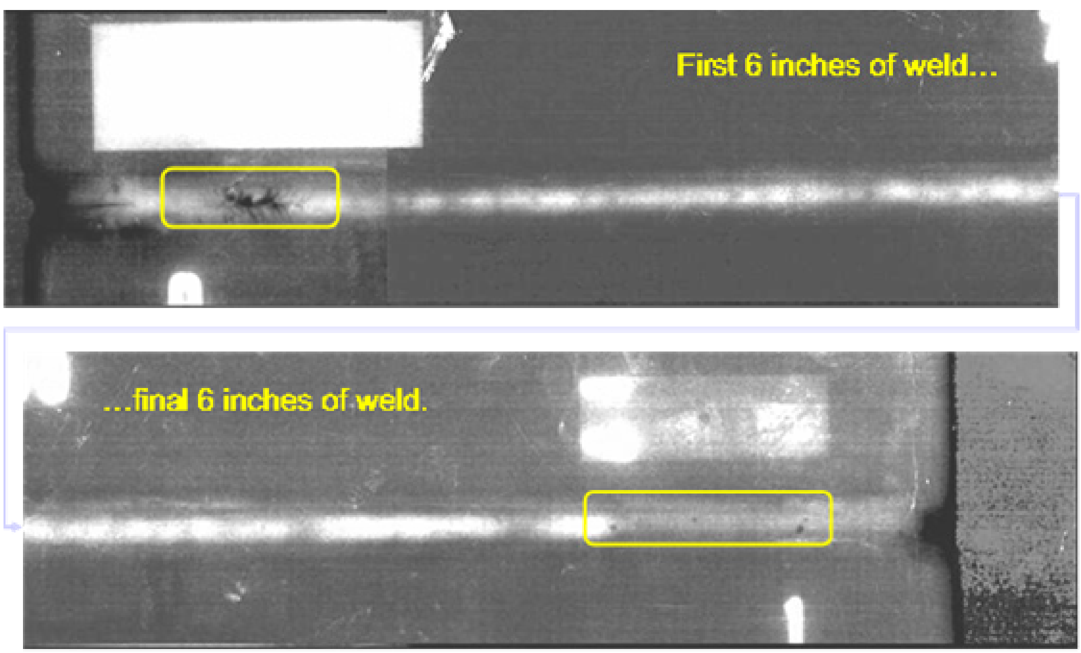
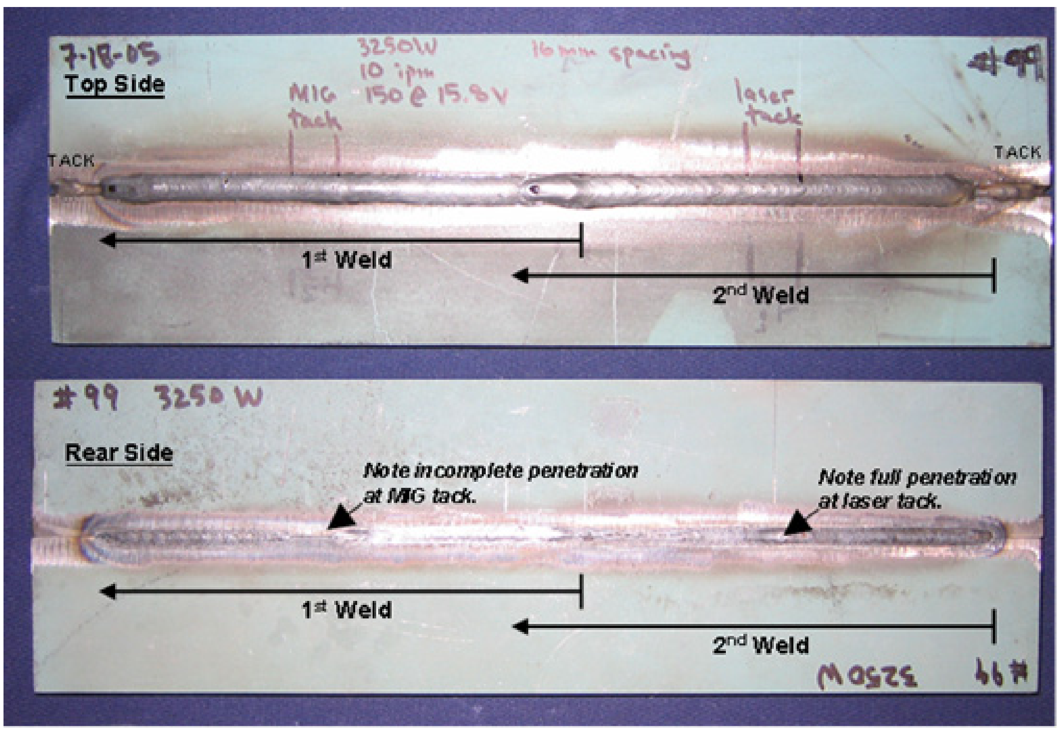


Figure **27**. Radiographic testing of hybrid weld in 12.7 mm (0.5 inch) thick mild steel reveals small amount of porosity confined to regions near the beginning and end.

Tack Welds and Overlaps

In most practical applications of hybrid welding of thick sections, such as pipe welding, it can be expected that parts will be fit-up and tack welded prior to final processing. A concern is that the hybrid welding process must be able to maintain quality as tack weld regions are processed. An additional practical concern in circumferential pipe welding is that adequate weld quality must be maintained in the overlap region as the end of the weld crosses over the weld start.

An experiment was performed to investigate (a) the ability to hybrid weld through tack welds and (b) the overlap region (see Figure **28**). The figure shows both the front and backside of welds performed over both a GMAW tack weld (with additional filler material), and a laser tack weld (without additional filler material).



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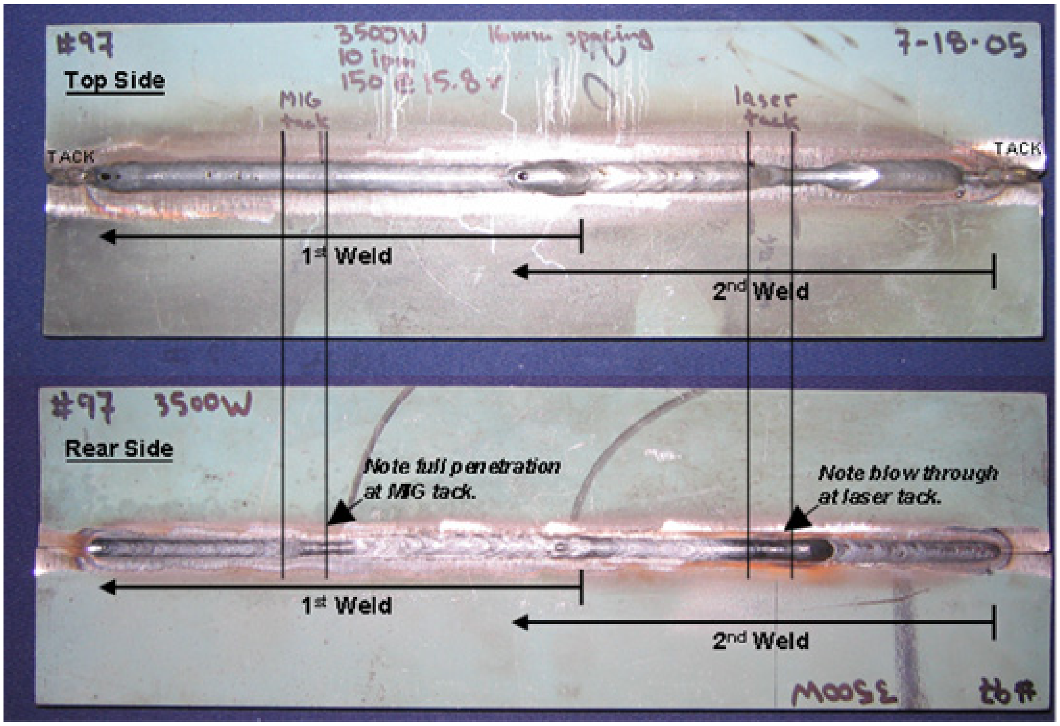

Figure **28**. The front and backside of two experiments to (a) investigate the ability to weld over tack welds and (b) determine issues involved in weld overlap (necessary for circumferential pipe welds).

At a laser power level of 3.25 kW, the weld appears to be acceptable as the process crosses over the laser tack weld, but incomplete penetration was noted in the GMA tack weld region. An increase in power to 3.5 kW provided full penetration at the GMA tack weld, but resulted in backside blow-through at the laser tack weld (the plate was still hot). Though more extensive testing is certainly warranted, it is encouraging that conditions can be found which appear to produce acceptable welds in both cases.

Due to the large spacing between the laser and GMAW torch, it was deemed acceptable to start the welds with ~10 mm of a full penetration laser weld only, before the GMAW joined the process. This seems to allow for acceptable overlap—both overlaps showed indications of full penetration. Again, these results are preliminary and additional testing was conducted throughout the remainder of the project.

Welding with Gap and with Distant Laser-to-GMAW Torch Spacing

Through the course of these experiments, certain advantages in a distant spacing between the laser and the GMAW torch have become apparent, such as the ability to produce full penetration welds at higher speeds and the seeming intolerance to process variations. However, a serious concern is whether or not this distant spacing still offers any benefit over autogenous laser welding in processing gaps within the joint.

An experiment was performed in which a gap of 0.75 mm was intentionally introduced into the joint (see Figure **29**). (It should be noted that for pipe, commercial-off-the-shelf technology can provide joint preparations with 0.13 mm (0.005 inch) flatness.) Though full penetration was achieved with acceptable topside bead geometry and reinforcement, the weld suffered from undercut due to inadequate backside reinforcement. Additional work is required to determine the limits of gap tolerance with distant laser-to-GMAW torch spacing.

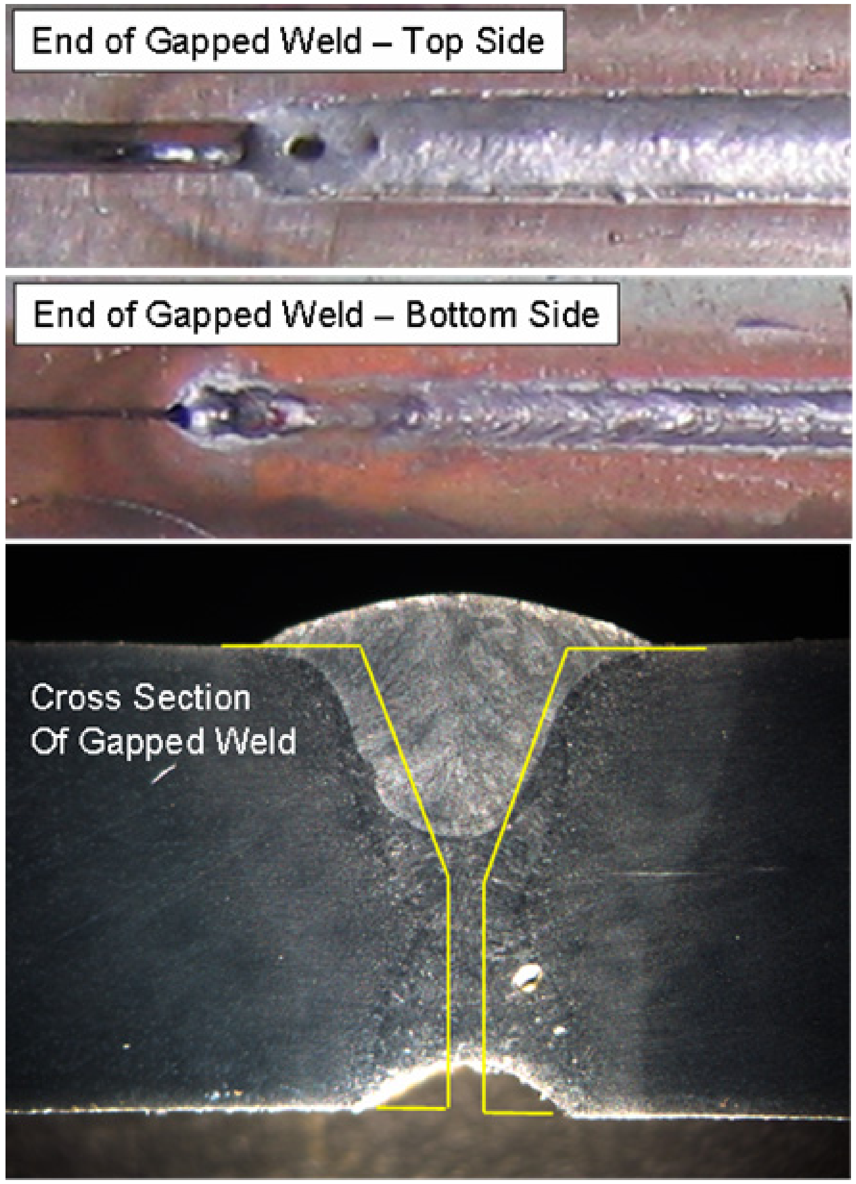

Figure **29**. Results of experiment to investigate ability of 16 mm laser-to-GMAW torch spacing hybrid weld to accommodate a 0.75 mm (0.03 in) gap (10 mm thick, 5 mm land, 40º included angle, 10 ipm travel speed, 150 ipm WFS).

Phase I Discussion and Conclusions

Conventional hybrid welding stipulates that the laser beam and the GMAW torch be spaced quite near to each other. For thick section welding, this has the advantage of resulting in complete mixing of the filler material throughout the fusion zone, and at slow speeds the direct combination of heat from the two processes that can result in full penetration. Additionally, one

would expect an increased tolerance to gaps. A disadvantage of near spacing, however, includes a seeming intolerance to process variations to enable full penetration while preventing backside blow-through. Additionally, the significant interaction of the two processes in close proximity may lead to difficulty in process development.

Utilizing hybrid welding with more distant spacing between the laser and the GMAW torch offers the advantages of both an ability to join thick sections at higher speeds and a robust tolerance to variations in travel speed. Additionally, development of process parameters may be a simpler task, since interaction between the two processes is limited. Potential disadvantages of increased spacing include a lack of mixing of the filler alloy throughout the thickness and a decreased ability to tolerate gaps in the joint. Hybrid welds in 12.7 mm (0.5 inch) thick steel plate with 16 mm spacing have been shown to possess adequate mechanical properties. Porosity at the start and end of the weld remains an issue.

Joint geometry has been shown to have a significant effect on the ability to provide adequate reinforcement coupled with full penetration and acceptable backside reinforcement. Narrow bevel angles seem to result in a reduced propensity for backside undercut.

It has been shown that process parameters can be developed that appear to enable adequate welding over both GMAW tack welds and laser tack welds. Weld overlap at the start and stop has also been demonstrated to produce seemingly acceptable weld quality. In both cases, additional testing is warranted.

Phase II Experiments at ARL Penn State

Phase II Experimental Objective

A series of experiments were run to further investigate the impact of various parameters on the laser-GMA hybrid welding process for the eventual single-pass pipe welding application described earlier. In this case, thickness was reduced from 0.5 inch (12.7 mm) to 0.25 inch (6.35 mm), and only straight butt welds were investigated. The effect of laser-to-GMAW torch spacing was more closely explored to determine if a process using closer spacing (2–6mm) could be optimized to achieve full penetration without excessive backside blow-through. Additionally, changing the direction of travel so that the GMAW torch was leading the laser beam was tested

and compared to laser-leading processes. Finally, practical aspects of hybrid welding, such as welding over tack welds, overlap of weld start and stop (required for circumferential pipe welds), and gap tolerance were investigated further.

Technical Details

A variety of laser-GMA hybrid welds were performed using a combination of a Trumpf diode-pumped 4.5 kW Nd:YAG laser and a Lincoln Electric PowerWave 455 STT GMAW power supply (operated in both constant voltage and pulsed mode). The laser and GMAW torch head were configured as previously shown in Figure **16**. The welds were performed on 0.25 inch (6.35 mm) thick mild steel (A36) straight butt joints using ER70S-6 filler wire at a diameter of 0.045 inch (1.1 mm). For shielding, an Ar-10% CO_2 shield gas was supplied through the GMAW torch nozzle. Unless otherwise noted, the laser was operated at 4.5 kW with focal at the top surface of the plate or at the bottom of the bevel.

Phase II Experimental Results

Parameter Optimization

After testing a number of parameters at laser-to-GMAW torch spacing of 2–6 mm, welds were achieved with full penetration and acceptable backside blow-through at a spacing of 4 mm. Selected welds are shown in Figure **30**.

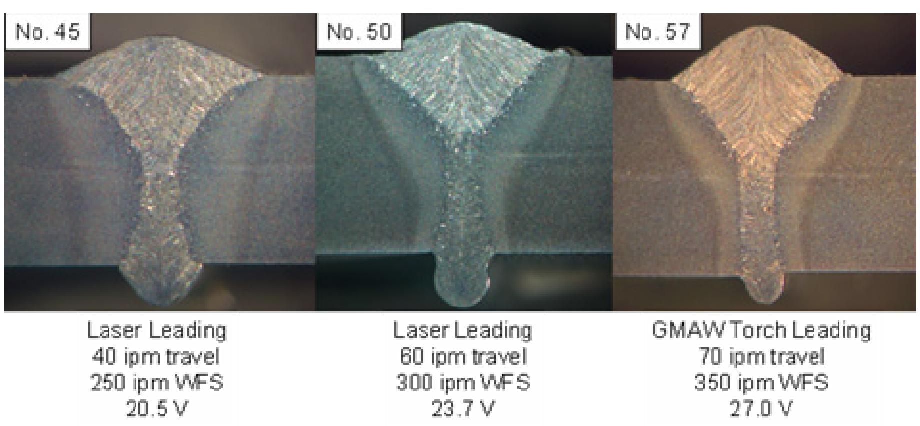

Figure **30**. Full penetration welds achieved at a variety of optimized processing conditions in 0.25 inch thick steel plate.

These welds represent the highest quality welds that were achieved, and were obtained with both laser-leading and GMAW torch-leading configurations. Through extensive experimentation, a variety of trends were observed which could serve to guide parameter development for alternate plate thicknesses and weld geometries.

GMAW Torch Positioning

Acceptable welds were achieved in both laser- and GMAW torch-leading configurations. Figure **31**, a diagram of the positioning of the laser beam and GMAW torch relative to the direction of travel, shows how the torch is in a "pushing" position when the laser is leading the GMAW torch and a "pulling" position when the GMAW torch is leading the laser[3].

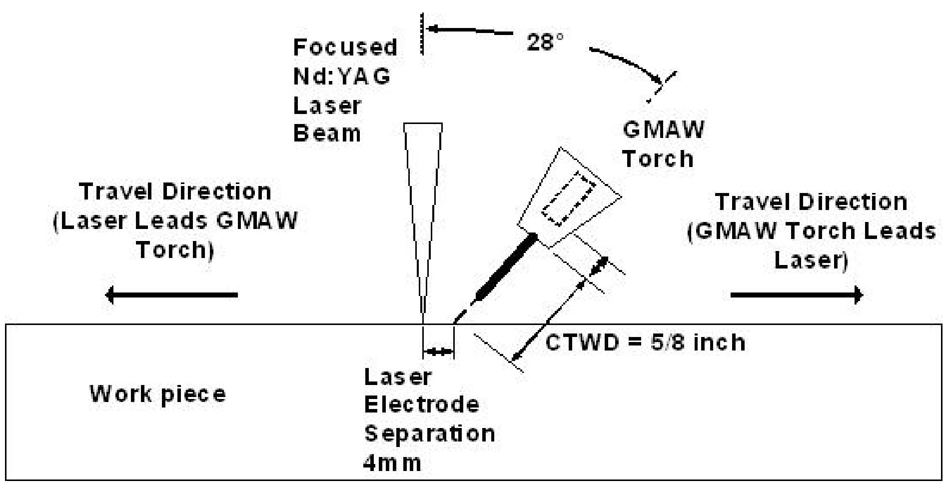

Figure **31**. Positioning of the laser beam and GMAW torch relative to the direction of travel.

The position of the GMAW torch, whether "pushing" or "pulling", affected the shape of the weld bead and fusion zone. Figure **32** shows a number of GMA-only welds to compare the bead shape of torch "pushing" vs. torch "pulling" welds. Note that the wire feed speed and travel speed are modified in tandem to deliver a constant volume of weld metal per unit length.

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[3] Note that "pushing" and "pulling" welding configurations are often referred to as forehand and backhand torch orientation, respectively.

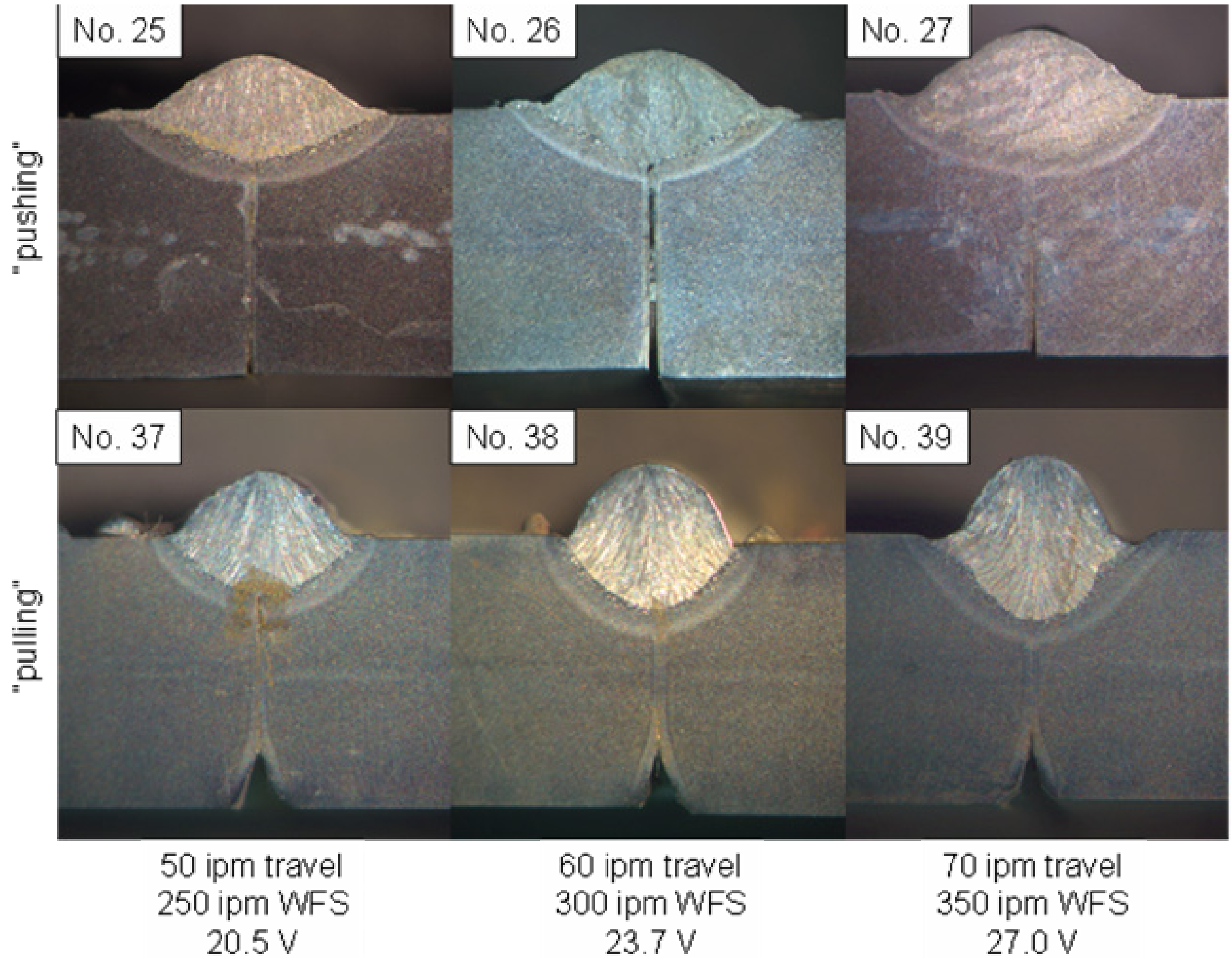

Figure **32**. Comparison of bead shape between torch “pushing” and torch “pulling” GMAW-only welds at a variety of processing conditions.

The torch “pushing” welds (top row) are clearly wider than the “pulling” welds (bottom row), which are narrower and slightly taller. In “pushing” welds, the molten metal is forced to the leading edge of the weld pool, leading to a wider and flatter bead. Conversely, “pulling” welds push molten metal toward the back of the weld pool, tending to produce more convex, narrower beads [7].

Laser-leading vs. GMAW Torch-Leading

This change in bead shape is also observed, though to a lesser extent, when the laser is added to the process to execute hybrid welds with either laser-leading (torch "pushing" configuration) or GMAW torch-leading (torch "pulling" configuration). Figure **33** shows cross sections of hybrid welds using the same GMAW parameters as the welds in Figure **32**, but with the addition of 4.5 kW of laser power. Note that whenever the welds exhibited blow through and intermittent rear side humping, sometimes referred to as "string of pearls", the cross sections were located to cut through the areas of significant drop through. For these experiments, the laser energy serves to provide additional heat that leads to hotter and flatter bead profiles than observed with GMA welding alone. Laser-to-GMAW torch spacing is 4 mm.

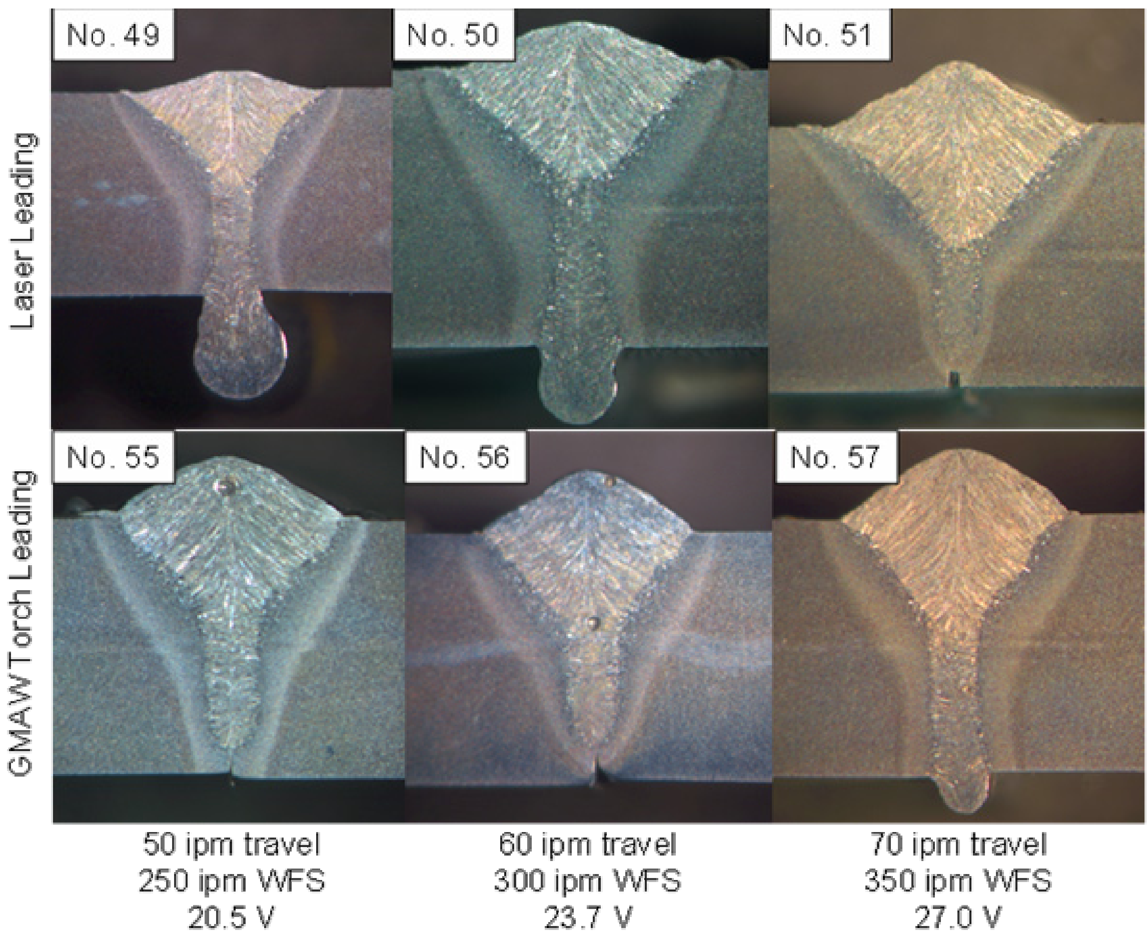

Figure **33**. Laser- vs. GMAW torch-leading configurations at relatively high travel speeds.

In addition to the difference in bead shape between laser- and torch-leading hybrid welds, Figure 33 (above) and Figure 34 (below) also show the impact of laser- and torch-leading configurations on weld penetration. At slower travel speeds 0.5–1.1 m/min (20–40 ipm), shown in Figure 34, both configurations achieve full penetration. However, at speeds of 1.3–1.8 m/min (50–70 ipm), as shown in Figure 33, laser- and torch-leading welds exhibit different penetration characteristics.

For laser-leading welds in this range, penetration trends are similar to those of autogenous laser welds in that higher speeds tend to eventually lead to reduced penetration. As travel speed is increased the heat input per unit length is decreased, resulting in decreased penetration and an inverse relationship between travel speed and penetration. The addition of filler material does not serve to impede laser beam penetration because the laser is leading the metal deposition from the arc weld.

Conversely, the addition of filler material plays a much larger role in penetration for torch-leading hybrid welds, and does not exhibit a simple inverse relationship between travel speed and penetration. Full penetration was achieved at slower travel speeds 0.5–1.1 m/min (20–40 ipm), shown in Figure **34**, but not in the 1.3–1.5 m/min (50–60 ipm) range. The additional filler material introduced by the GMA torch ahead of the laser-beam interferes with beam penetration, which explains the decreased penetration compared to laser-leading welds. Surprisingly, full penetration was again achieved at 1.8 m/min (70 ipm). One explanation for the increased penetration at this speed is that at higher travel speeds the filler and surrounding material ahead of the laser beam have not yet had time to cool significantly and thus remain at a temperature high enough to improve laser penetration despite the fact that there is more material to penetrate. This would explain why a torch-leading weld has greater penetration than a laser-leading weld at 1.8 m/min (70 ipm).

Weld Width at Lower Travel Speeds

When welding at lower travel speeds, the heat input per unit length is sufficient to result in significant intermittent blow-through on the backside of the weld, i.e. string of pearls (see Figure **34**). Additionally, as speed is decreased below 40 ipm (1.1 m/min), the internal fusion zone width tends to increase. This seems to indicate that with high enough heat input per unit length,

the keyhole effect is less pronounced and substrate melting is achieved primarily through conduction from the build up of heat being delivered to the substrate rather than through direct interaction with the laser beam energy. This phenomenon is observed in both laser- and GMAW torch-leading configurations.

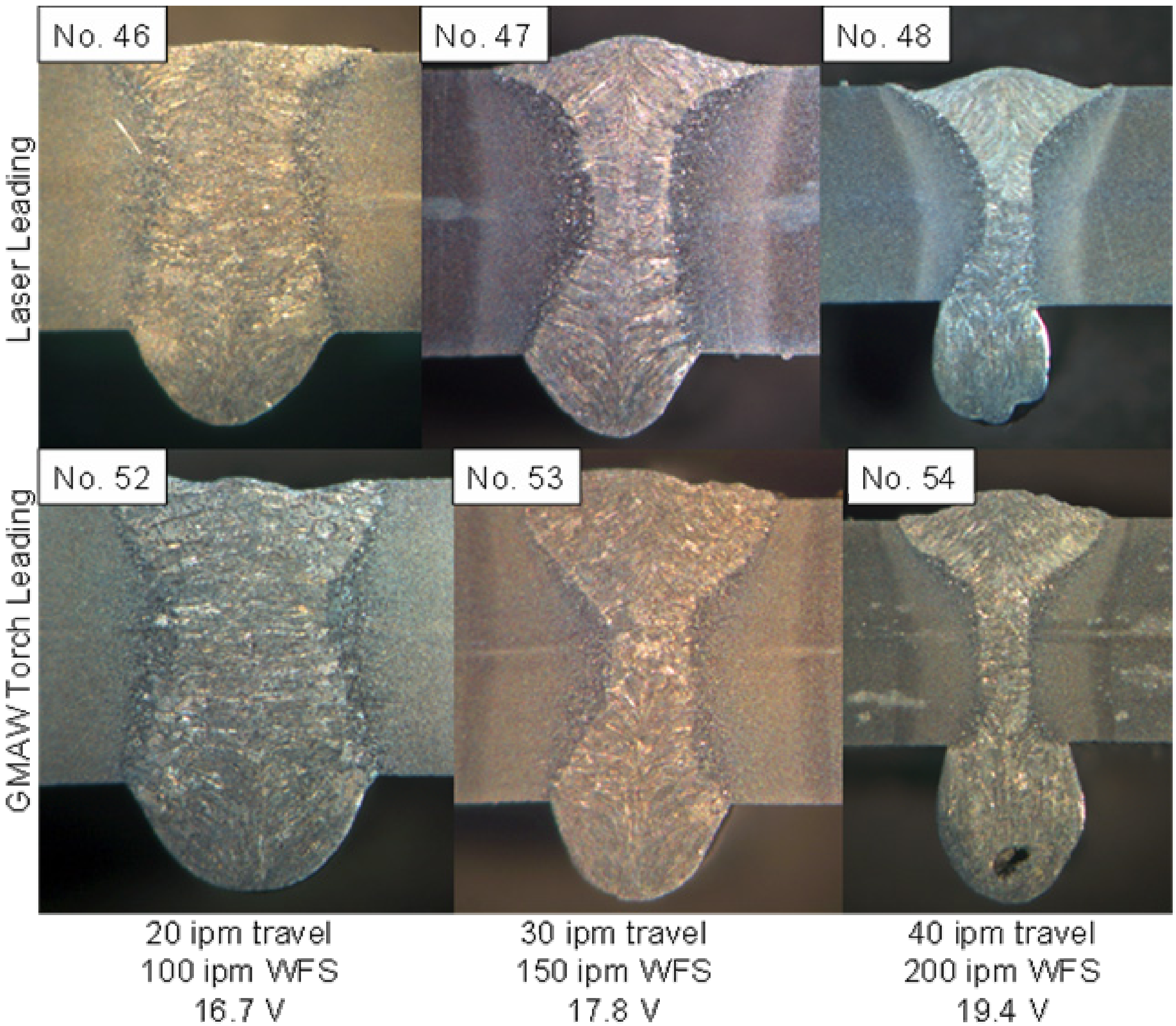

Figure **34**. Laser- vs. GMAW torch-leading configurations at reduced travel speeds.

Welding in Pulsed Mode

Many GMAW power supplies now come standard with pulsed welding mode selections. These modes are generally used to reduce overall heat input during welding. They also serve to

simplify the GMAW parameter selection process by defining presets, such as voltage, that require that the operator set only a single parameter, typically WFS. This is in contrast to standard constant voltage (CV) welding mode, which requires both WFS and weld voltage be set. The effect that the addition of a laser had on the process was observed by comparison to comparable CV-mode parameters, Figure 35 and Figure 36.

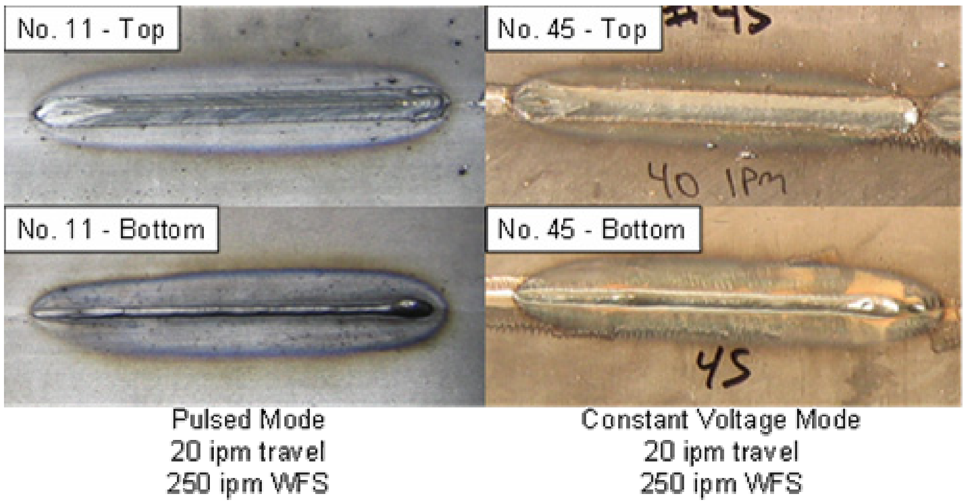

Figure **35**. Pulsed mode vs. Constant Voltage Mode at low travel speed.

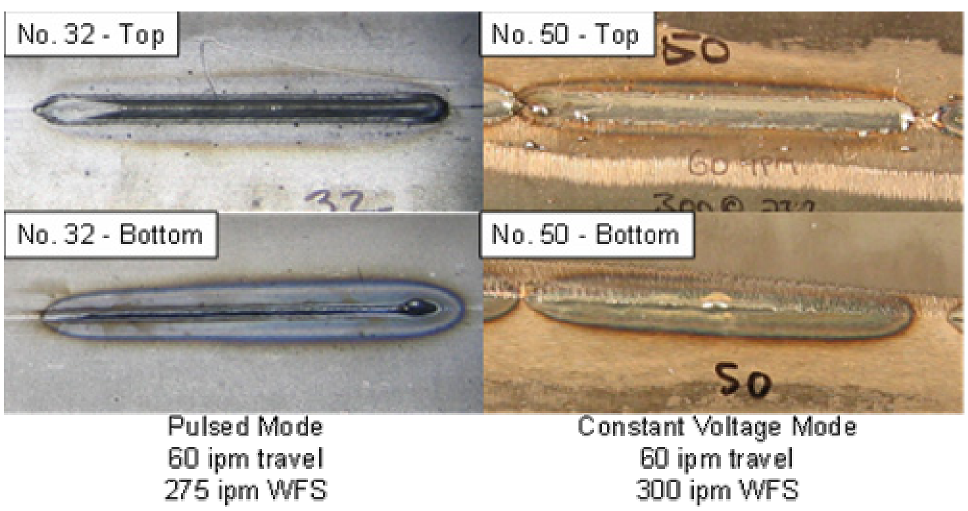

Figure **36**. Pulsed mode vs. Constant Voltage Mode at high travel speed.

In both cases, the pulsed mode produced high quality and, in some cases, more consistent weld beads on both the top and bottom surface of the weld. If hybrid welding is being introduced to an application to reduce heat input in order to limit distortion, then pulsed mode welding is worthy of consideration.

Welding Over Laser and GMA Tack Welds

A practical aspect of hybrid welding that must be considered in industrial applications is the ability of the process to produce quality, full penetration welds as tack welds are encountered during the joining process. To investigate this, the GMAW process was used to introduce tack weld metal deposition that approximated the GTAW tack welds utilized in the NASSCO pipe shop. It was observed that hybrid welding soon after the tack welding process often resulted in blow-through, evident in Figure 37, apparently the result of an excess of heat build-up in this region. Conversely, when the tack welds are allowed to cool, consistent weld beads are produced. This emphasizes the delicate nature of the process, and the balance of factors that must be maintained to produce quality welds.

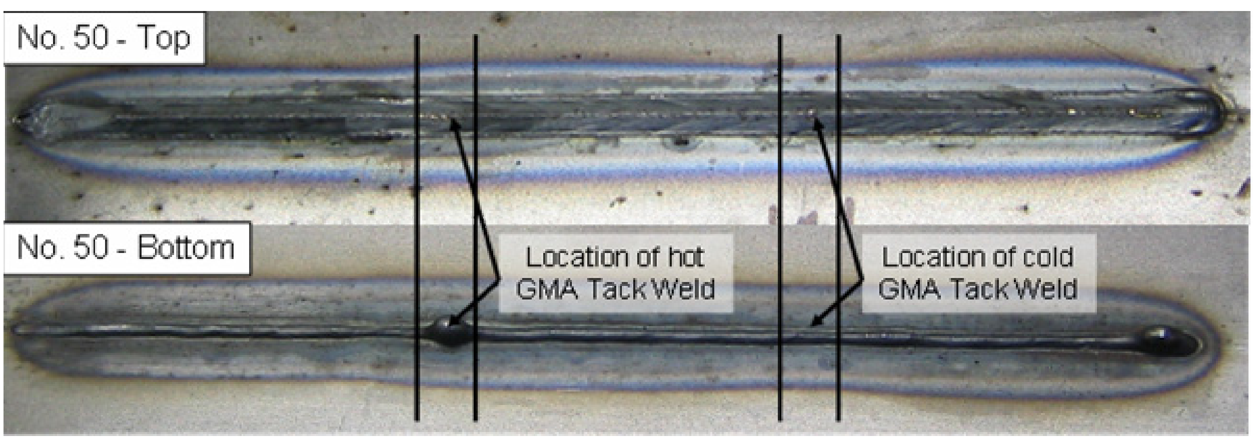

Figure **37**. Blow-through resulting from hybrid welding over a hot GMAW tack welds.

Gap Tolerance

Another practical consideration in introducing the hybrid process to industrial applications is the ability to produce quality welds in the face of changing joint gap. The ability of hybrid welding to deal with gaps more effectively than laser welding alone has been a strong motivator for use

of the process. In an industrial application, it is conceivable that gap widths would vary throughout the weld. A single set of processing conditions to accommodate this condition is necessary to mitigate the need for complex and expensive sensor feedback and real-time parameter adjustment. To evaluate the robustness of the hybrid welding process in the face of changing gap, two plates, one without a gap and one with a 0.5 mm (0.020 inch) gap (maintained through the use of shim stock located at the beginning, middle, and end of the weld), were joined using the same hybrid welding parameters. The results are shown in Figure 38.

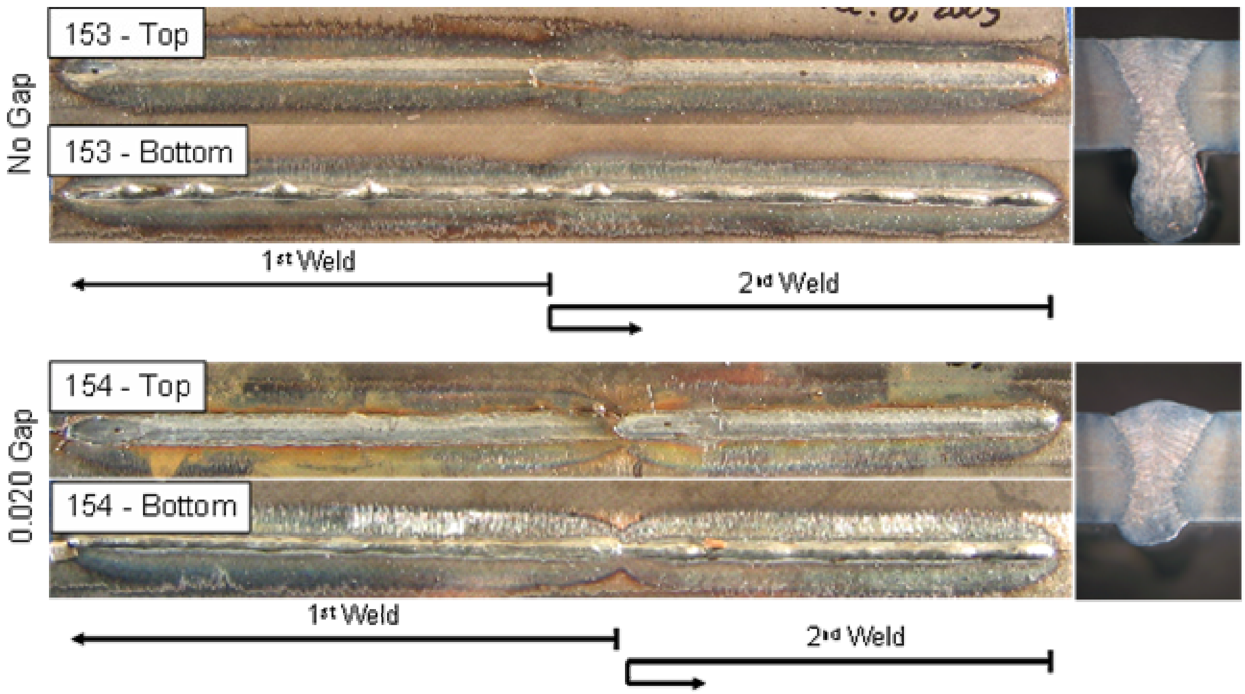

Figure **38**. Introduction of a relatively small gap affects the weld quality on the backside of the weld.

In this case, parameters that produced a consistent, quality weld in the presence of a gap resulted in an inconsistent, poor quality weld when the gap was eliminated. Though it is clear that a single set of parameters is not robust in this case, continuing efforts seek to investigate this further.

Laser Power Ramping

In previous experiments, radiographic inspection revealed porosity at the beginning of the hybrid weld. This condition has been observed in laser welds, and can often be attributed to dynamic instability as the keyhole is developed. A common solution is to ramp the energy density in a controlled fashion, typically by ramping laser power. Experiments were undertaken to evaluate the effectiveness of this technique in hybrid welding. Laser power ramping may also serve to eliminate blow-through sometimes experienced during the weld overlap required for pipe welding. It was found that laser power ramping can be used to control penetration and blow-through and results are pending for porosity analysis of welds utilizing laser ramping at the start and finish.

Ceramic Backing

Practical application of hybrid welding requires process robustness in the face of tack welds, overlap, and gap variation. Though adequate penetration can easily be assured with sufficient power, unacceptable backside blow-through is often the result, as shown in Figure **39**.

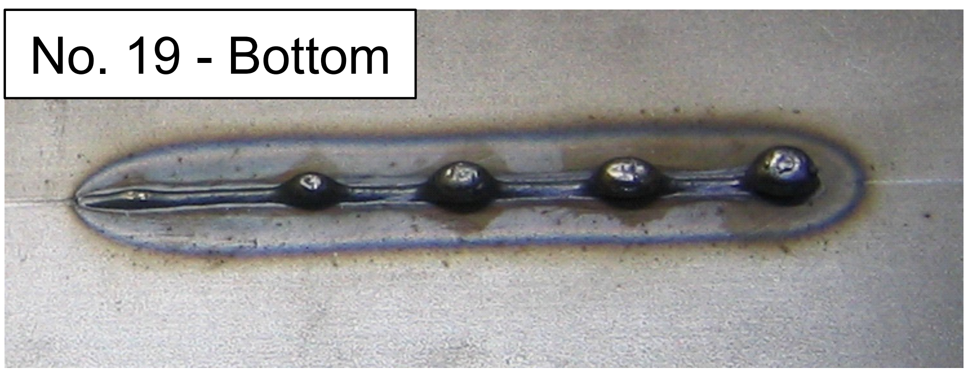

Figure **39**. Example of backside blow-through when heat input is too high.

To address the blow-through issue, ceramic backing was applied to hybrid welds conducted using a variety of different processing conditions (see Figure 40). In this case, a hybrid weld ~250 mm (10 inches) in length was executed, and ceramic backing tape was applied only to the middle section of the weld, to enable direct comparison to weld quality produced without ceramic backing.

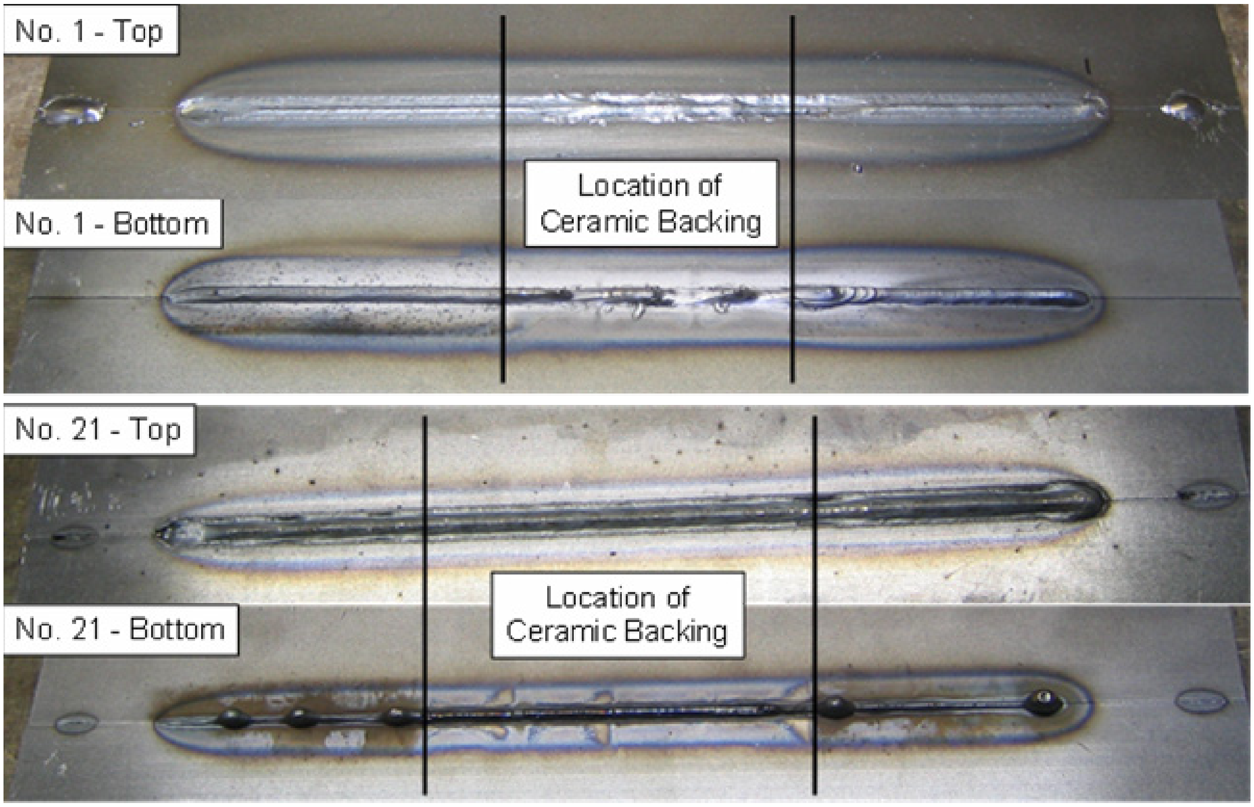

Figure **40**. Two welds that employ ceramic backing in the middle third of the weld.

From the figure, it appears that for weld conditions that would normally exhibit small backside reinforcement (weld no. 1 above), ceramic backing leads to instability and a reduction in weld quality. This likely results from the thermal insulation that the backing provides, which would lead to higher temperatures and a more viscous melt pool.

However, in welds with increased backside reinforcement or backside blow-through, the ceramic backing results in a more consistent and higher quality weld (weld no. 21 above). Though offering potential benefit by ensuring process robustness, it is likely economically or technically undesirable to utilize ceramic backing in many applications, such as pipe welding.

Phase II Summary and Conclusions

A series of experiments were run to further investigate the impact of various parameters on laser-GMA hybrid welding. Additionally, practical aspects of hybrid welding, such as welding over tack welds, overlap of weld start and stop (required for circumferential pipe welds), gap tolerance, and techniques to control blow-through were investigated.

The effect of laser-to-GMAW torch spacing, which had a significant effect on previous experiments, was explored for straight butt welds in 0.25 inch (6.35 mm) thick plate steel. Multiple processes were developed using a laser-to-GMAW torch spacing of 4 mm which achieved full penetration without excessive backside blow-through and complete mixing of filler material throughout the fusion zone.

Changing the configuration so that the GMAW torch was leading the laser beam was evaluated and compared to laser-leading processes. GMAW torch-leading hybrid processes had different bead shapes and exhibited somewhat non-intuitive penetration trends compared to laser-leading processes using identical processing parameters. At 4 mm laser-to-GMAW torch spacing, the highest travel speed full-penetration weld was achieved using a torch-leading process.

Using a GMAW power supply in pulsed mode produced high quality hybrid welds with a reduced heat input that may be especially beneficial for limiting distortion in certain applications. In many cases, hybrid welds using the pulsed mode had more consistent beads on both the top and bottom surface of the weld than welds using comparable constant voltage parameters.

Consistent hybrid welds with full penetration were achieved over GMA tack welds. However, when tack welds were not allowed enough time to cool off before hybrid welding, significant backside blow-through occurred at the tack weld.

Process parameters were developed which could produce an acceptable quality hybrid weld with a 0.5 mm (0.020 inch) gap. Unfortunately, the parameters that produced a consistent, quality weld in the presence of a gap resulted in an inconsistent, poor quality weld when the gap was eliminated. Though a single set of parameters was not robust in this case, further efforts sought to investigate this further.

Laser power ramping was able to control penetration and blow-through for a hybrid welding process.

Ceramic backing was applied to hybrid welds conducted using a variety of processing conditions. For weld conditions that would normally exhibit small backside reinforcement, ceramic backing leads to instability and a reduction in weld quality likely due to thermal insulation. However, in welds with significant backside blow-through the use of ceramic backing resulted in consistent, high quality welds. For some applications ceramic backing may be effective in ensuring process robustness.

This series of experiments successfully produced consistent, high quality welds in 0.25 inch mild steel flat butt joints using several different sets of process parameters. It was shown that consistent welding over tack welds, in the overlap of welds, and with the presence of a 0.5 mm (0.020 inch) gap are all possible using different parameters.

Phase III Experiments at GD NASSCO

Substantial effort to develop hybrid welding process parameters for various thicknesses of flat steel plate was undertaken prior to completion of the hybrid pipe welding system. However, once the pipe welding system was available, additional process parameter evaluations on pipe were required to help ensure a robust process and to learn of other process variations by the transition from welding plate to pipe. A portion of the more important experimental results are presented below.

Unless otherwise noted, in all experiments the weld was performed in a 1G horizontal rolled position. The seam tracker was 25 mm ahead of the 200 mm focal length laser beam, which was 25 mm ahead of the GMAW torch.[4] The laser impinged the pipe 35 mm ahead of top-dead-center, in order to produce a flatter and smoother topside reinforcement. Additionally, the pipes were fit and tack welded with 20–25 mm long autogenous GTAW tack welds, i.e. without filler wire addition, in order to ensure a consistent volume of material for the laser penetration. The

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[4] Separating the laser-to-GMAW torch, as in subject configuration, is sometimes referred to as tandem laser-GMA welding rather than hybrid laser-GMA welding, and enables the use of an argon plasma suppression nozzle without detrimental affect to the GMAW shielding gas.

pipe was specified according to ASTM A53, the GMAW filler wire was 1.1 mm (0.045 inch) diameter ER70S-6, and the GMAW shield gas was Ar-10%CO_2. The pipe diameter and wall thickness, i.e. pipe schedule, are noted, and two 150 mm (6 inch) lengths were joined for the experiments (though only a 25 mm wide section cut around the weld is shown).

Variation in Root Face Height

In the first experiment, involving 8 inch SCH 80 pipe, substantially the same processing conditions and joint bevel angle were used in each case, and variation in land height was investigated. All three land heights produced acceptable topside and bottomside weld beads, though the small land height exhibits slight undesirable undercut at the root. This is because the vapor keyhole has fully penetrated, resulting in expulsion of molten material through the root into the inside of the pipe. In contrast, the larger land heights produce excellent rootside reinforcement, and though full penetration is achieved, seemingly the vapor keyhole does not fully penetrate and so surface tension forces act to maintain the rootside reinforcement — the vapor keyhole does not cause material expulsion through the root. In the case of small land height, the laser energy per unit volume seemingly exceeds that required to melt the volume of material that must be melted to achieve full penetration.

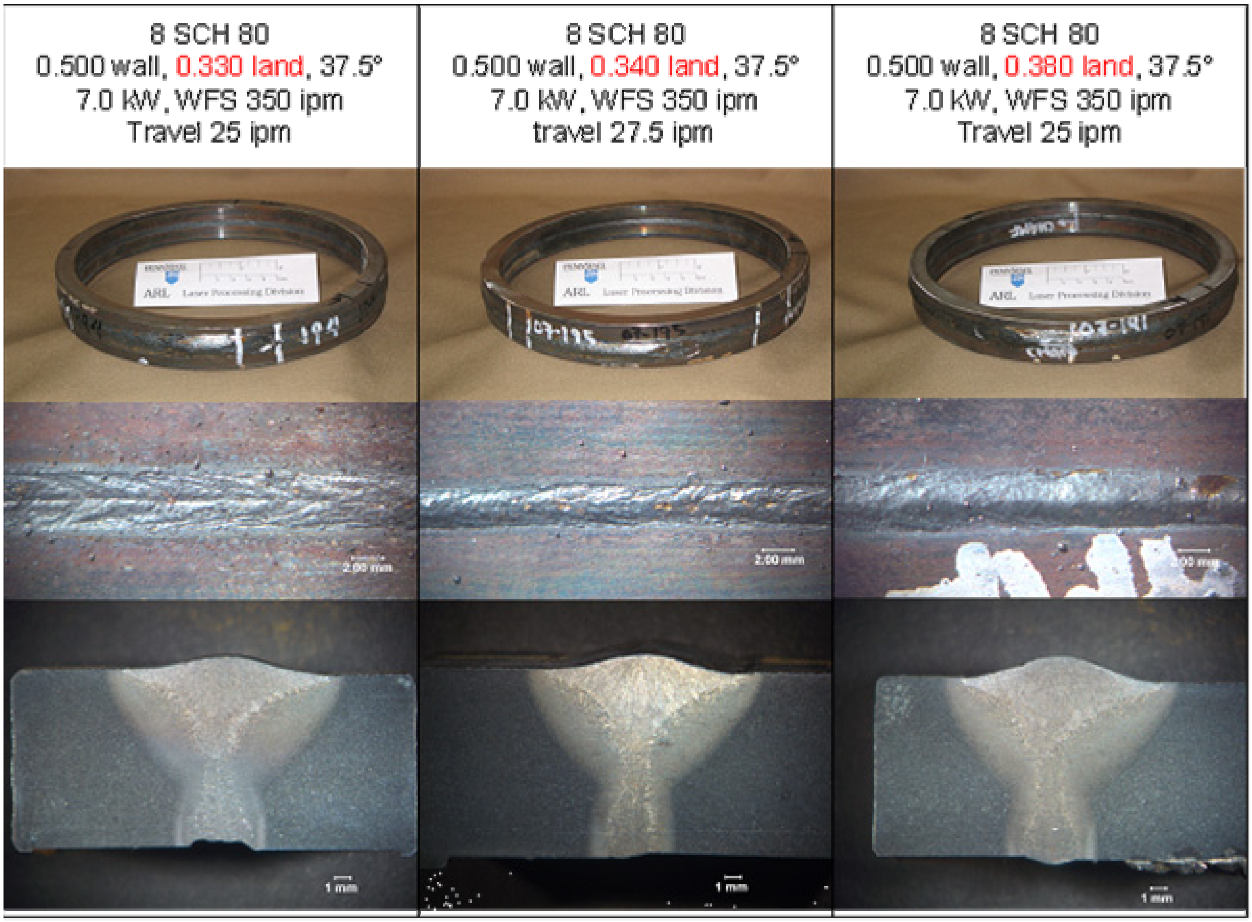


Figure **41**. Investigation of varying land height. The welded pipe is shown, with close-ups of the rootside reinforcement and macro sections.

Variation in Laser Power

In the second experiment, involving 6 inch SCH 40 pipe, the same processing conditions and joint geometry were used in each case, and variation in laser power was investigated. Again, all three exhibit acceptable topside and rootside reinforcement, but the two higher power conditions result in slight undesirable undercut at the root. This is again caused by full penetration of the vapor keyhole and expulsion of material through the root. Evidence of this is readily observable in the form of small beads of metal which come from the opposite side of the pipe interior. Again, the laser energy seems to be higher than necessary to melt the correct amount of material. These last two experiments suggest that a simple way to ensure a robust process would be "overpowering" the process, i.e. providing more laser energy than is necessary to melt just the

minimum amount of material to achieve full penetration. It is likely that this may not be the case for other alloy systems.

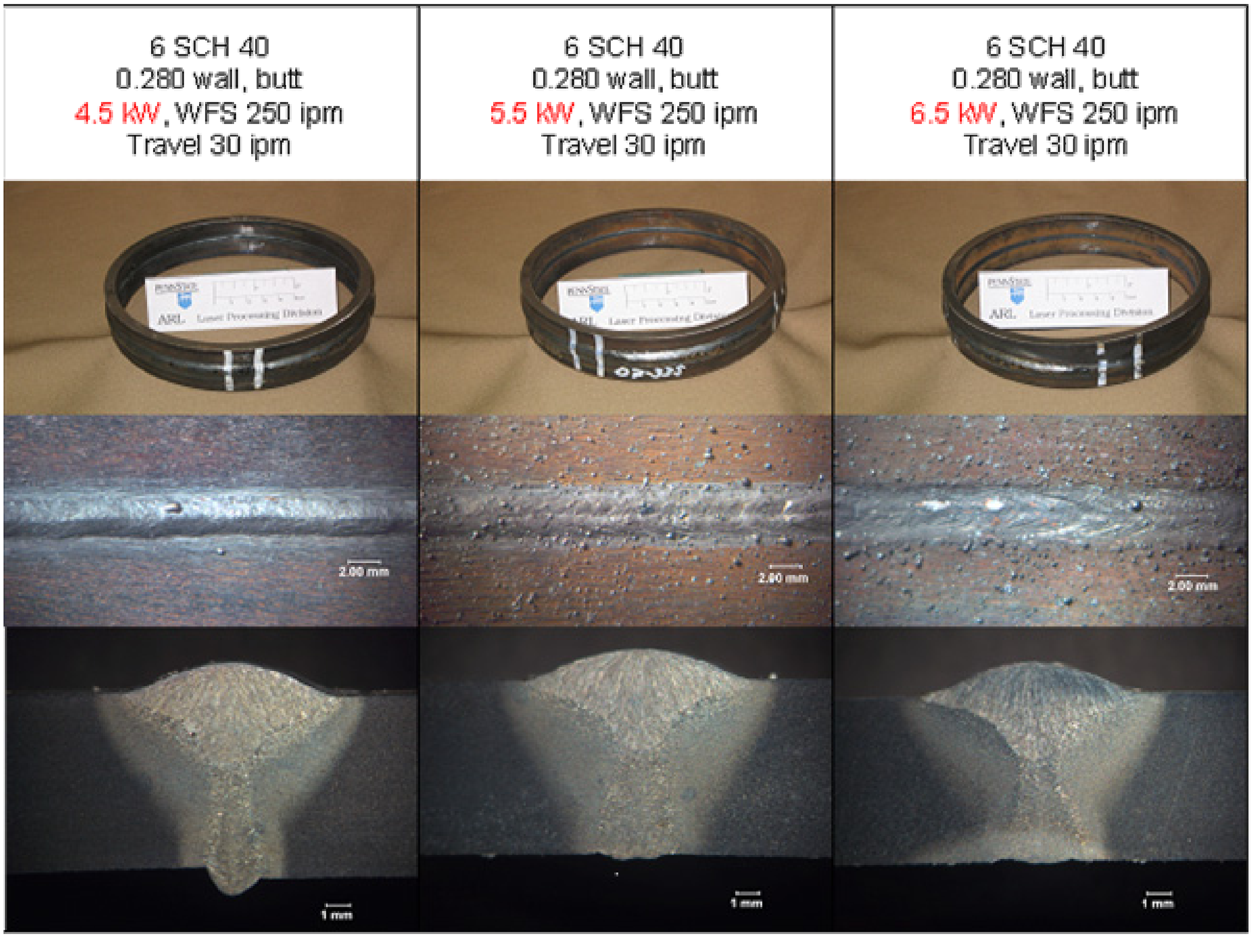


Figure **42**. Investigation of varying laser power. The welded pipe is shown, with close-ups of the rootside reinforcement and macro sections.

Variation in Bevel Angle

In the third experiment, involving 8 inch SCH 80 pipe, substantially the same processing conditions and land height were used in each case, but the bevel angle was varied. In past work, variations in bevel angle have been known to occasionally result in changing melt characteristics, e.g. melting of the bevel sidewall, with attendant variability in penetration characteristics. Additionally, wider bevels will require additional material to adequately fill the joint. Given this, it is unexpected that all three bevel angles produce comparable, high quality weld beads,

though that is what is observed in this case. This is likely due to the relatively small proportion of the bevel relative to the overall wall thickness, so that the fill volume varies little with respect to the volume of the added filler material.

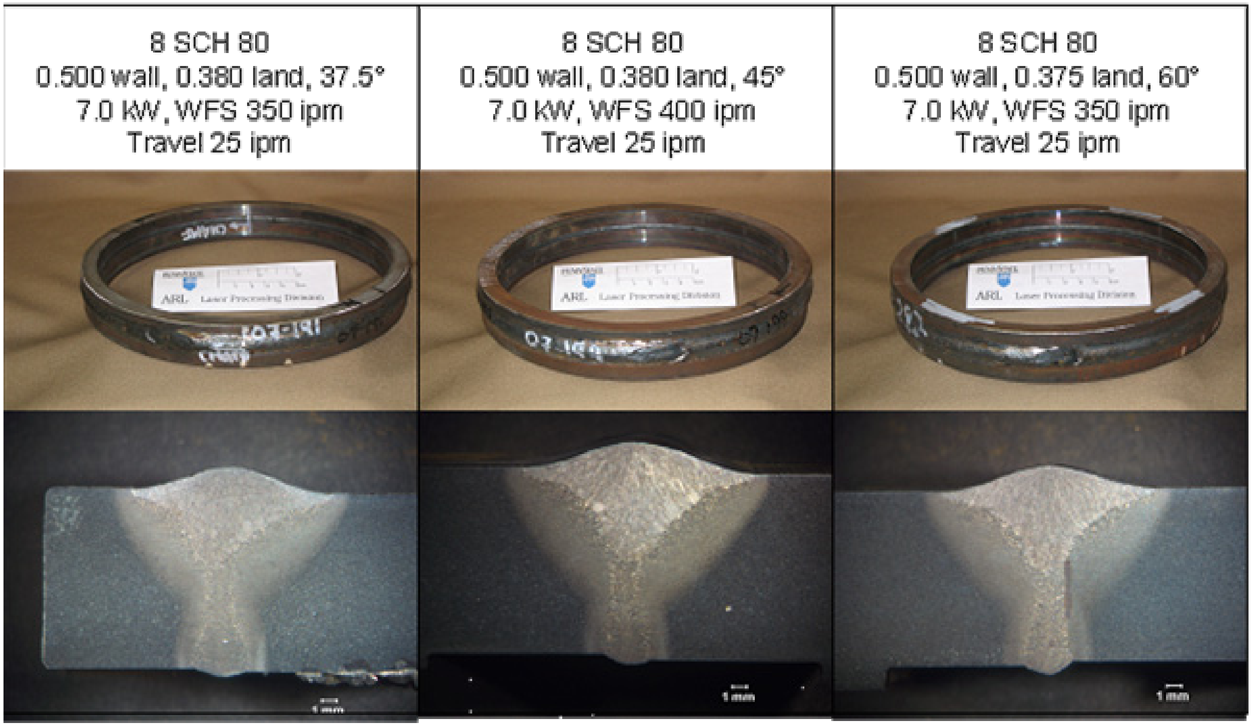


Figure **43**. Investigation of varying bevel angle. The welded pipe is shown, with macro sections.

Variation in Laser Stand-Off

In the fourth experiment, involving 6 inch SCH 40 pipe, the same processing conditions and joint geometry were used in each case, but the laser stand-off was varied. The nominal stand-off places the focal point of the beam squarely at the surface of the pipe (or on the bottom of the bevel, when bevels are used in thick wall pipe). In this case, when beam irradiance is at a maximum at the surface, full penetration of the vapor keyhole and resultant material expulsion is evident in the backside reinforcement. However, taking the laser beam slightly out of focus seems to reduce the irradiance such that full vapor keyhole penetration is not realized, with the resultant improved rootside reinforcement geometry.

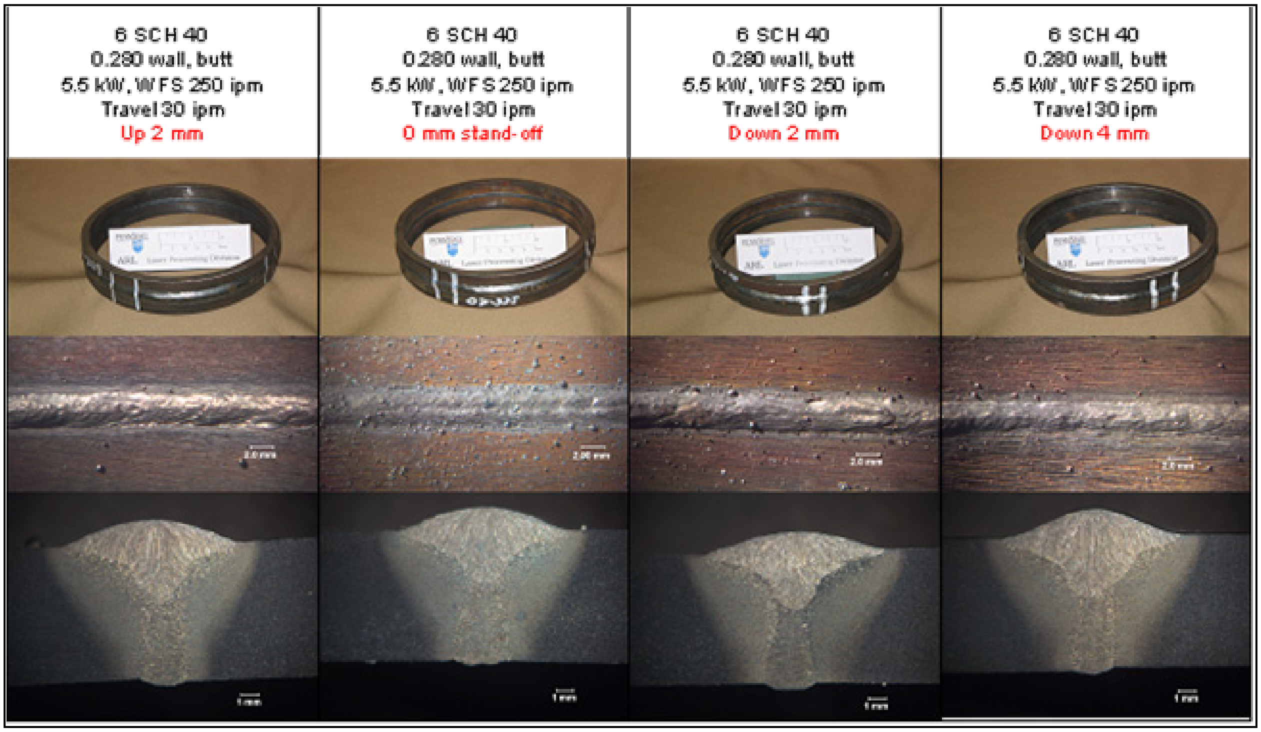


Figure **44**. Investigation of varying laser stand-off. The welded pipe is shown, along with close-ups of backside reinforcement and macro sections.

Phase IV Copper Nickel Pipe Experiments

Though comparably little effort was spent in welding copper nickel (CuNi) pipe, the results of experiments to address this important area are presented below.

Background

CuNi pipe is used in certain ships for seawater and drainage piping. For a given shipset, the number of welds for various diameter pipe are listed below:

- 2-3 inch 325 joints
- 3-4 inch 124 joints
- 4-5 inch 97 joints
- 5-6 inch 71 joints
- 6-7 inch 19 joints

The weld procedure involves a root pass, then additional passes no thicker than 0.080 inch at 3 ipm travel speed for manual passes to fill the joint, then 2 passes for a finishing pass (> 0.25 inch wide). Between passes, the welder must wait until interpass temperature is 150°F. If fit-up is poor, than the interpass temperature must fall to room temperature for any quarter circumference section of pipe. To accomplish this, the weld operation is stopped after 1/6th circumference has been welded to allow the part to cool. This helps with the quality of the backside. Based on this information, an interpass wait time assumed to be 15 minutes, and an assumed single pass hybrid weld at 40 ipm, the cost savings calculations presented in Table 1 were produced. Based on these figures and an assumed burdened labor cost of $100/hr, it can be estimated that single pass hybrid pipe welding of CuNi pipe may produce savings up to $128,000 per ship set. For this reason, it was determined that preliminary investigation into potential for hybrid welding to join CuNi pipe was warranted.

Experiments

Initial tests utilized the Trumpf 4.5 kW Nd:YAG laser located at ARL Penn State to produce autogenous laser welds in CuNi plate provided by General Dynamics Electric Boat (GDEB). In this case, the maximum available laser power was utilized, and travel speed was varied to produce welds in both 0.250 inch thick and 0.500 inch thick sections. The results for 0.25 inch thick plate are presented in Figure 45. Full penetration with no evidence of porosity is achieved up to 45 ipm travel speed. At speed below 30 ipm, the weld sags and unacceptable undercut is present at the top of the weld. For the 0.500 inch thick plate, no welds achieved full penetration, and a bevel similar to that used in the steel pipe experiments is expected to be required to achieve single pass welding. It was anticipated that similar results would be achieved when combined into a tandem hybrid weld on pipe.

Table 1. CuNi pipe estimates hybrid weld savings.

Given	Given	Given	Given	Assu med	Assu med	Table Look Up	Table Look Up	Calcu-lated	Calcu-lated	Calcu-lated	Calcu-lated	Calcu-lated	Calcu-lated	Assumed	Calcu-lated	Calculated	Calcu-lated
	Number of Welds per Ship Set	Weld Thickness per Pass	Weld Travel Speed	Inter-pass Wait Time	1/6 Circumference Wait Time	Low End Pipe Thickness (SCH40)	High End Pipe Thickness (SCH80)	Average Diameter	Average Thickness	Average Number of Passes	Circumference (Average Pipe Diameter)	Weld Time per Pass	Total Weld Time	Single-Pass Hybrid Weld Travel Speed	Hybrid Weld Time	Time Saved per Weld	Time Saved per Ship Set
		{inch}	{inch/min}	{min}	{min}	{inch}	{inch}	{inch}	{inch}		{inch}	{min}	{min}	{inch/min}	{min}	{min}	{min}
2-3 inch	325	0.080	3.0	15.0	5.0	0.145	0.300	2.5	0.223	5	7.85	2.62	103.09	40	0.20	102.89	33440.4
3-4 inch	124	0.080	3.0	15.0	5.0	0.216	0.337	3.5	0.277	6	11.00	3.67	126.99	40	0.27	126.72	15712.8
4-5 inch	97	0.080	3.0	15.0	5.0	0.237	0.375	4.5	0.306	6	14.14	4.71	133.27	40	0.35	132.92	12893.3
5-6 inch	71	0.080	3.0	15.0	5.0	0.258	0.432	5.5	0.345	7	17.28	5.76	160.32	40	0.43	159.89	11351.8
6-8 inch	19	0.080	3.0	15.0	5.0	0.280	0.500	7	0.390	7	21.99	7.33	171.31	40	0.55	170.76	3244.5
																Total Time Saved {min}:	**76642.9**
																Total Time Saved {hrs}:	**1277.4**

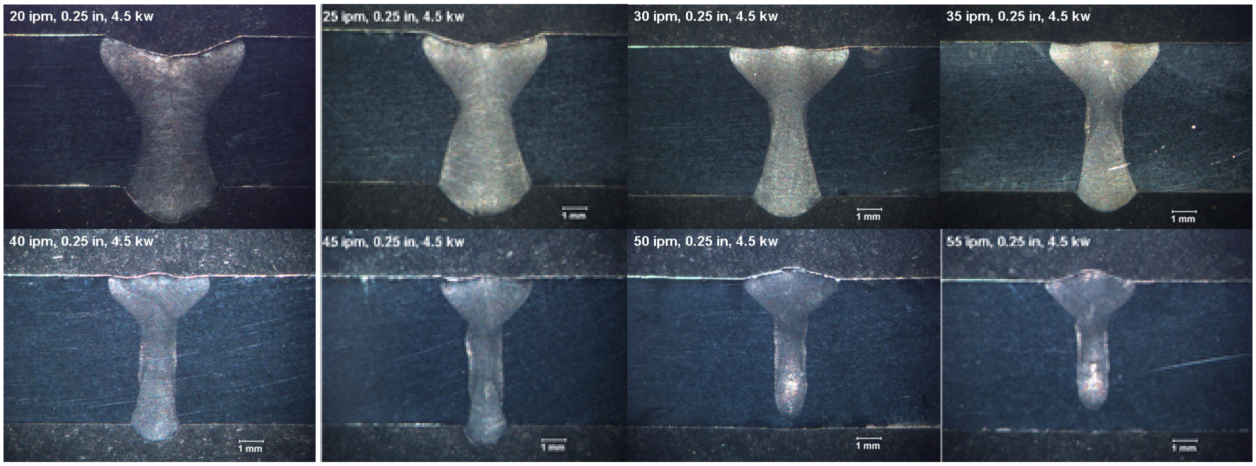


Figure 45. Autogenous laser welds at varying travel speed in 0.25 inch thick CuNi plate.

It was believed that the promising autogenous laser welding results would readily transfer to pipe when combined in the tandem hybrid configuration used for the steel pipe welding, i.e. with spacing of 25 mm (1 inch) between the laser and GMAW torch. Additionally, the experience gained in extensive steel pipe tandem hybrid weld development activities combined with the use of special synergic pulse weld schedules with the Fronius power supply built into the Hybrid Pipe Welding System were thought to ensure a relatively simple parameter development cycle when the system was installed at NASSCO shipyard.

After pipe schedules for steel pipe up to 30 inch diameter were developed at NASSCO, hybrid welds were conducted at NASSCO shipyard using both 70-30 CuNi pipe provided by GDEB and 70-30 and 90-10 CuNi scrap pipe from NASSCO shipyard. Results proved to be substantially different than expected based on previous experience with steel pipe. The weld wire that was used, 0.045 inch diameter MIL-EN67 from Techalloy, was recommended by and purchased from GDEB. At the recommendation of shipyard weld engineers, several shield gases were tried, and ended up with 75% Ar – 25% He. Of note is that feeding of the soft CuNi wire often resulted in birdnesting, and special care should be taken in designing a wirefeed system as short as possible with a minimum of short radius bends to minimize this issue.

The results of several of the weld tests with the best appearance are presented below. In Figure 46 and Figure 47, welds of 4 inch pipe are shown, straight butt with 0.110 inch thick wall. For

both the 90-10 and 70-30 CuNi, it is immediately evident that porosity is found in the laser portion of the weld, and pinholes are present on both the top and bottom sides of the weld. Also evident in the second figure is the mismatch of the laser and GMAW torch. It is noted later that a lesson learned would be to develop improved designs or better calibration methods to ensure alignment.

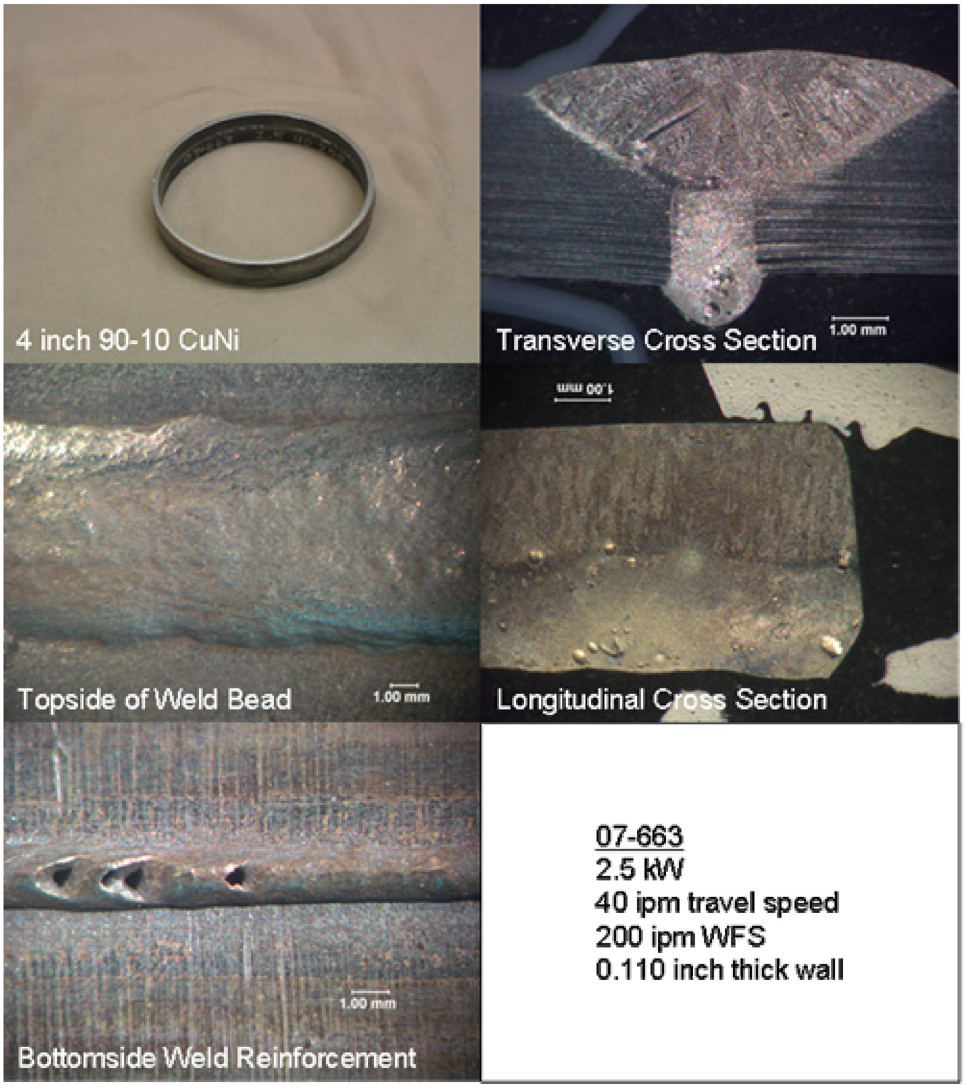


Figure 46. Tandem hybrid weld of 4 inch 90-10 CuNi pipe.

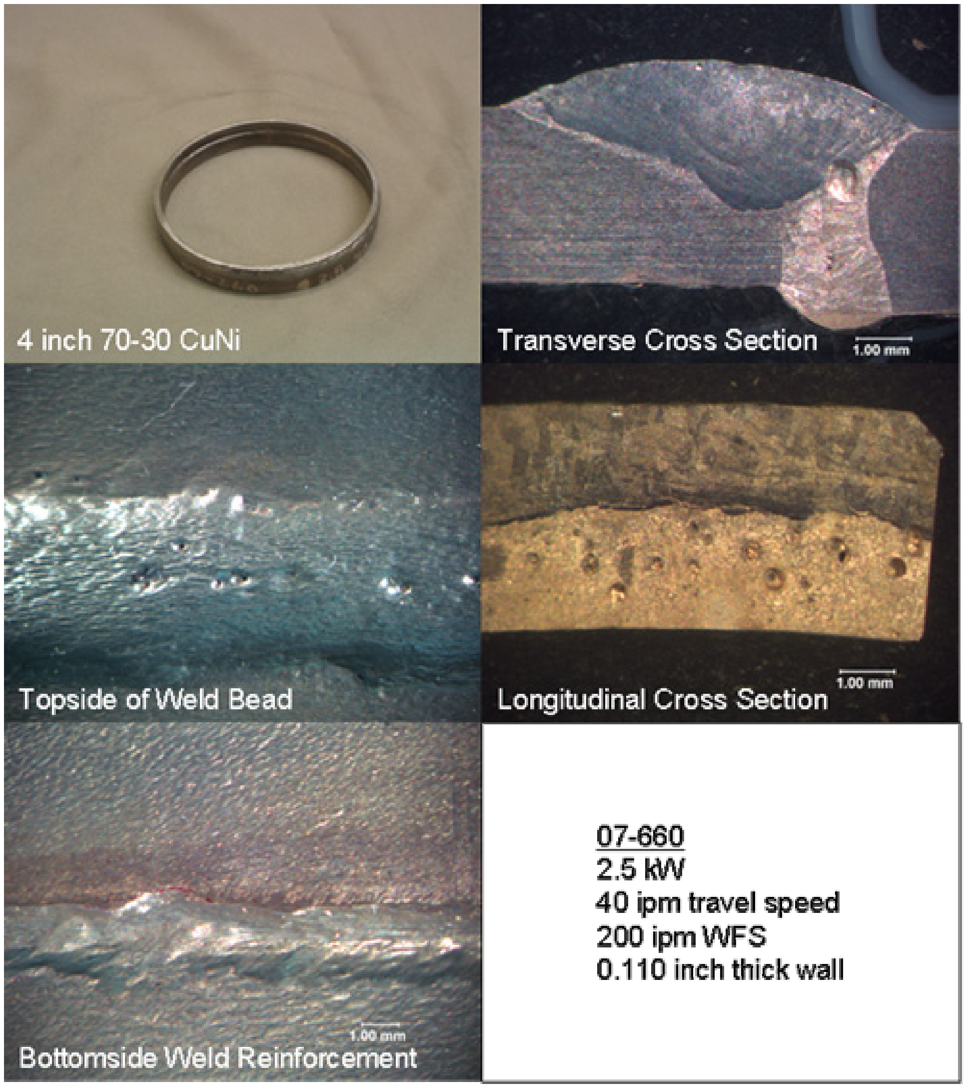


Figure 47. Tandem hybrid weld of 4 inch 70-30 CuNi pipe.

In Figure 48, 8 inch diameter 70-30 CuNi pipe is welded with a straight butt joint preparation and a 0.340 inch thick wall. Again, the mismatch in alignment between the laser and GMAW weld is immediately evident. And, though the weld was visually acceptable, substantial porosity is evident in the laser portion of the weld.

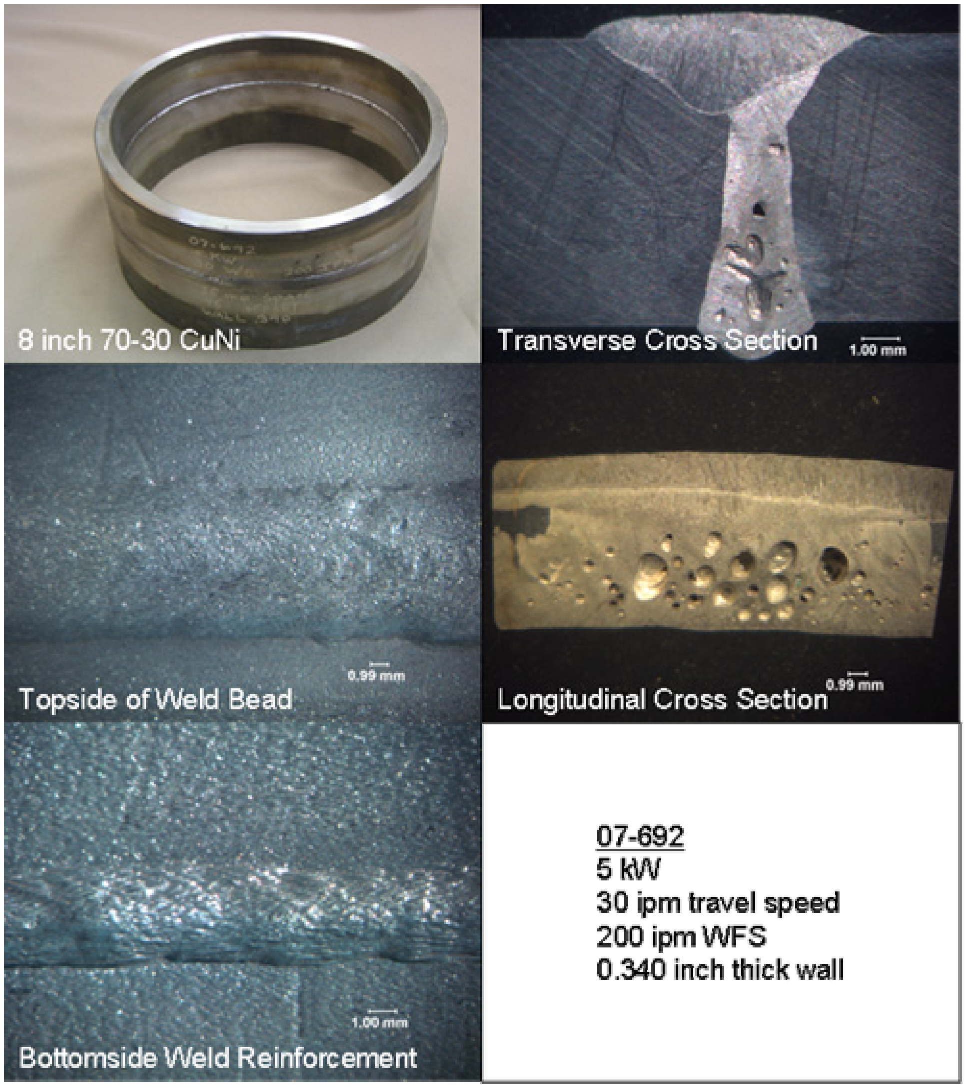


Figure 48. Tandem hybrid weld of 8 inch 70-30 CuNi pipe.

To combat the porosity, several things were tried including varying of laser power and travel speed, acid dipping the pipe after fit-up and immediately prior to welding, and back purging using Argon gas. None were successful in eliminating the porosity. The most likely explanation for the extreme porosity is the inclusion of relatively volatile elements in the pipe alloy which were not present in the plate material. It seems these elements are volatilized during welding due to the high temperature of the laser portion of the tandem hybrid weld, but do not have time to escape to the high cooling and solidification rates. Other possible explanations include the creation of keyhole instability, though this seems unlikely due to the sporadic shape of the

porosity and the fact that no porosity was evident in the plate welds over a wide range of travel speeds. It should be noted that only scant effort was applied to solving these issues, since the primary focus of the work was geared to welding steel pipe to support the cost benefit analysis and to prove ability to weld steel pipe over a wide range of diameters.

It is possible that welding in a "pure hybrid" mode, i.e. with laser impinging the filler material provided by the GMAW process rather than separated by 25 mm (1 inch), could help to mix in alloying elements which would prevent the formation of this porosity. Additionally, the extra heat may serve to keep the melt pool in a liquid state long enough for any gas that is formed to escape. Additional experiments are warranted to verify or disprove this theory.

ANCILLARY EXPERIMENTS

Process Gas Management

Management of process gases is an important part of developing a practical hybrid welding system and refers to the gas and air knives, jets, and nozzles used to control the gas, plasma, and spatter generated during the welding process. These gases must not negatively impact the GMAW shielding gas, which provides numerous functions required for adequate weld bead quality, and cannot be substantially disturbed. The effectiveness of the design is evaluated based on its ability to perform two main functions: plasma suppression and spatter control.

Plasma Suppression

A primary function of the gas management design is to suppress the plasma and gas plumes that are formed in the keyhole during laser welding. The plasma and gas plumes are generally directed by the keyhole directly along the laser beam path. This plasma absorbs and refracts the laser energy, and can result in substantial losses in the amount of laser energy available for welding, leading to a reduction in weld penetration. Plasma suppression gas has long been utilized for CO_2 laser beams, which operate at 10.6 μm in the far infrared portion of the electromagnetic spectrum and are know to be strongly absorbed in plasma. However, historically plasma suppression for lasers operating at 3 kW or less in the near infrared, i.e. Nd:YAG at 1062 nm, is often not considered important, since absorption by the plasma at the shorter wavelength is much reduced. However, we found that at the high powers provided by the 7 kW fiber laser, plasma suppression at these wavelengths did produce a noticeable increase in penetration.

To limit effects of the energy-absorbing plasma plume the plasma suppression gas should incorporate an element to blow the plasma and gas plumes out of the path of the laser beam. This element should be close to the work piece to limit the size of the plasma and gas plumes, as shorter plasma and gas plumes will absorb less laser energy. It is also important that this element use a gas which is not conducive to plasma formation and which does not have negative effects on the weld quality such as oxidation or porosity. A simple solution, implemented in the plasma suppression design used in this hybrid welding system, is a gas nozzle or jet aimed roughly

perpendicular to the plasma and gas plumes a short distance above the work piece, utilizing argon gas (with high ionization potential), and aimed so as not to disturb the GMAW shield gas.

Spatter Control

The second function of the gas management system is to protect the laser optics from being damaged by the spatter produced during the welding process. The laser optics are protected by a cover glass but if spatter sticks to the cover glass, the laser beam will heat the spatter until the cover glass is damaged and must be replaced. Frequent replacement of cover glasses can be costly, but a ruined cover glass during a weld will likely result in an unacceptable weld, wasting both time and material. For these reasons it is important that the spatter control system limit the amount of weld spatter reaching the laser optics.

Gas Management Experiments

Several elements may be used in a spatter control design to prevent damage to the laser optics. Air knives, nozzles, and jets are used to deflect the trajectory of the spatter away from the optics. Also, one or multiple apertures may be used to keep a majority of the spatter from coming near the optics. Figure **49** shows one example of such a set up using a simple aperture made by drilling a 0.25 inch aluminium plate, an air knife, and a nozzle made by flattening a copper tube. In this photograph, the air nozzle and air knife air directed toward the observer.

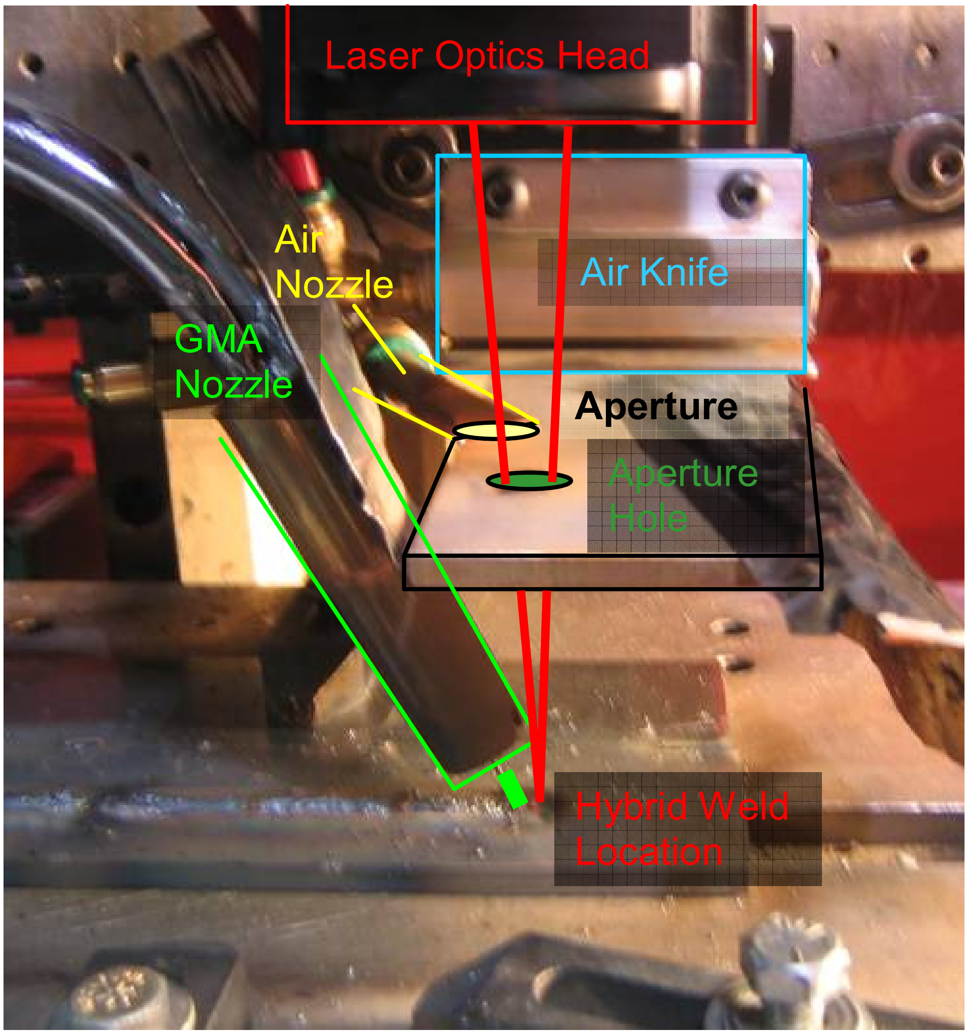


Figure **49**. Experimental setup for evaluation of gas management designs.

A series of experiments were conducted using the basic gas management design shown in Figure **49** varying the positioning of the air knife, using nozzles above, below, or above and below the aperture, and varying the air pressure to each element. A Mikrotron 1302 high speed digital camera, viewing the processing area from the right side of the figure, was used to record the performance of each configuration.

Figure **50** shows the effect of varying the air pressure through the air knife. The yellow line designates the direction of air flow from the air knife (right to left). The increasing air pressure leads to increased air velocity, which helps to deflect spatter. Also, the white gas plume coming

through the aperture decreased in height as the air pressure was increased since the air jet spreads along a wider path as it travels away from the air knife.

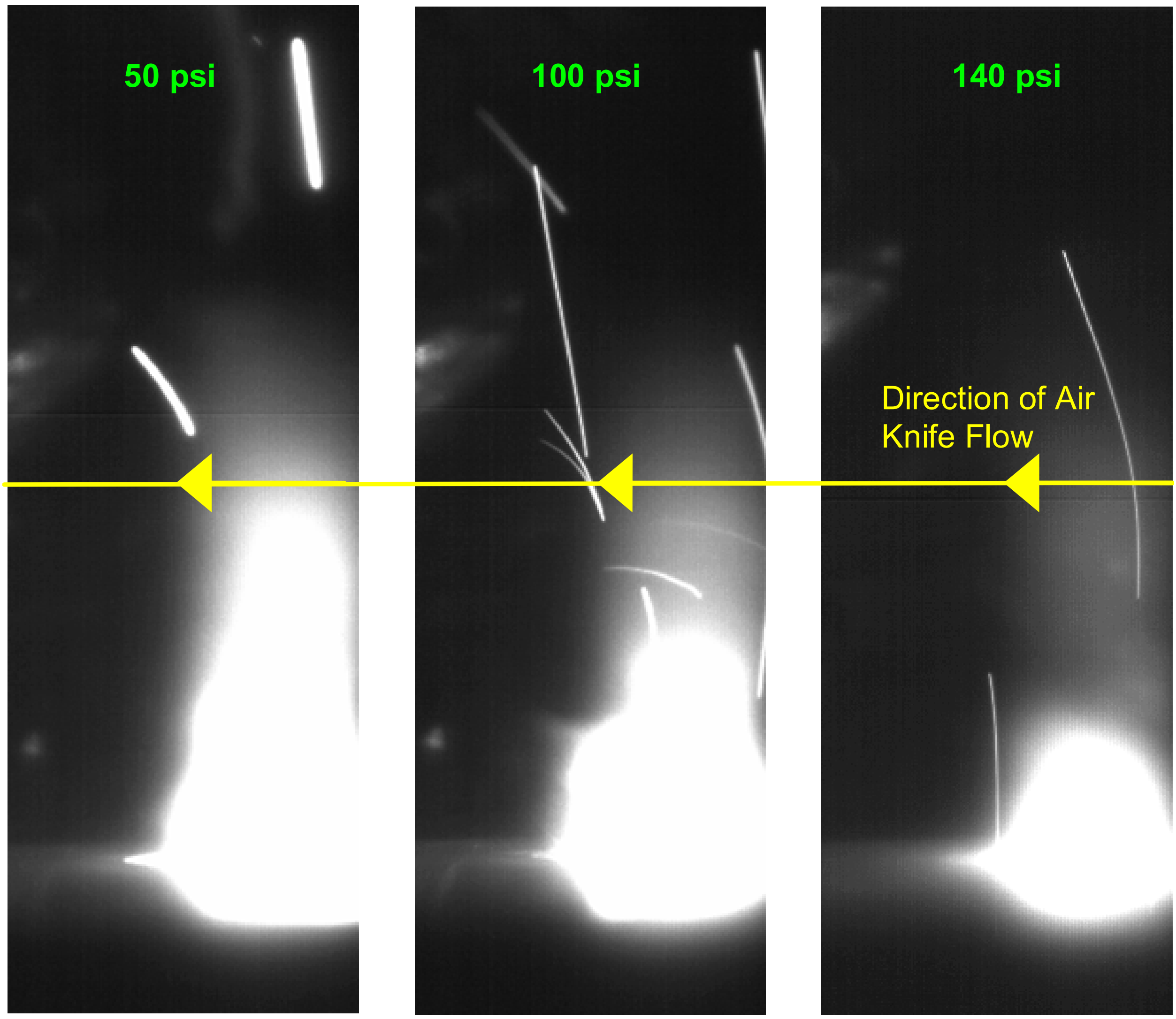


Figure **50**. Gas management with varying air pressure (Camera Aperture: 2.8, Exposure time: 1/1002 sec., framerate: 600fps).

Figure **51** shows the effect of varying the distance from the gas nozzle to the aperture hole. When the air knife is positioned closer to the aperture hole (right side of figure) the air is traveling at a higher velocity, and is thus more effective in deflecting the trajectory of spatter and the gas plume. When the air knife is at a more distant position from the aperture hole (left side of figure),

the air jet has spread out, providing a wider area of coverage and affecting the gas plume at a lower height, but the resultant reduction in gas velocity diminishes its ability to deflect the heavier spatter particles.

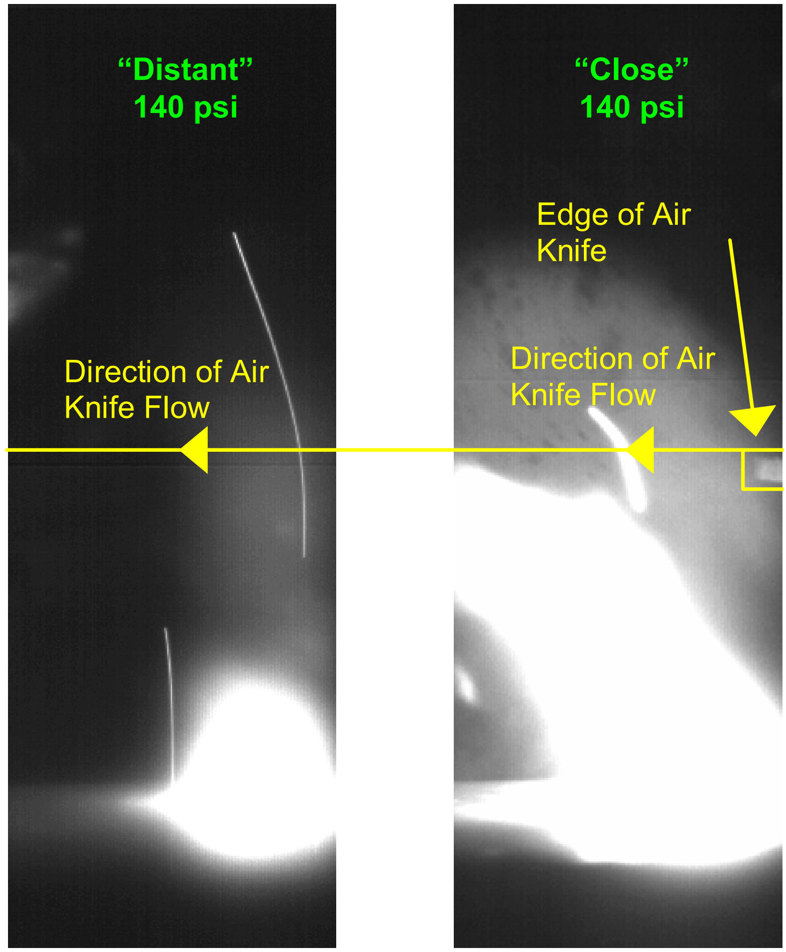


Figure **51**. Air knife at varying distance from aperture hole (Camera Aperture: 2.8, Exposure time: 1/1002 sec., framerate: 600fps).

Figure **52** shows the result of using an air nozzle in combination with an air knife. The left and middle pictures feature an air nozzle, with orange arrows indicating the patter of air flow, above the aperture but below the air knife, with yellow arrows indicating air flow from the air knife. The air nozzle produces a higher velocity flow of air which can be clearly seen in the drastic change of trajectory of spatter as it crosses the path of the air nozzle. The middle picture is useful

in comparing the impact of the air nozzle versus the air knife in deflecting spatter with the high velocity air nozzle clearly resulting in a greater change in the spatter trajectory. The right picture shows the effect of placing the air nozzle below the aperture which limited the height of the gas plume, which no longer passed through the aperture hole, but did not significantly limit the amount of spatter which traveled upward toward the air knife.

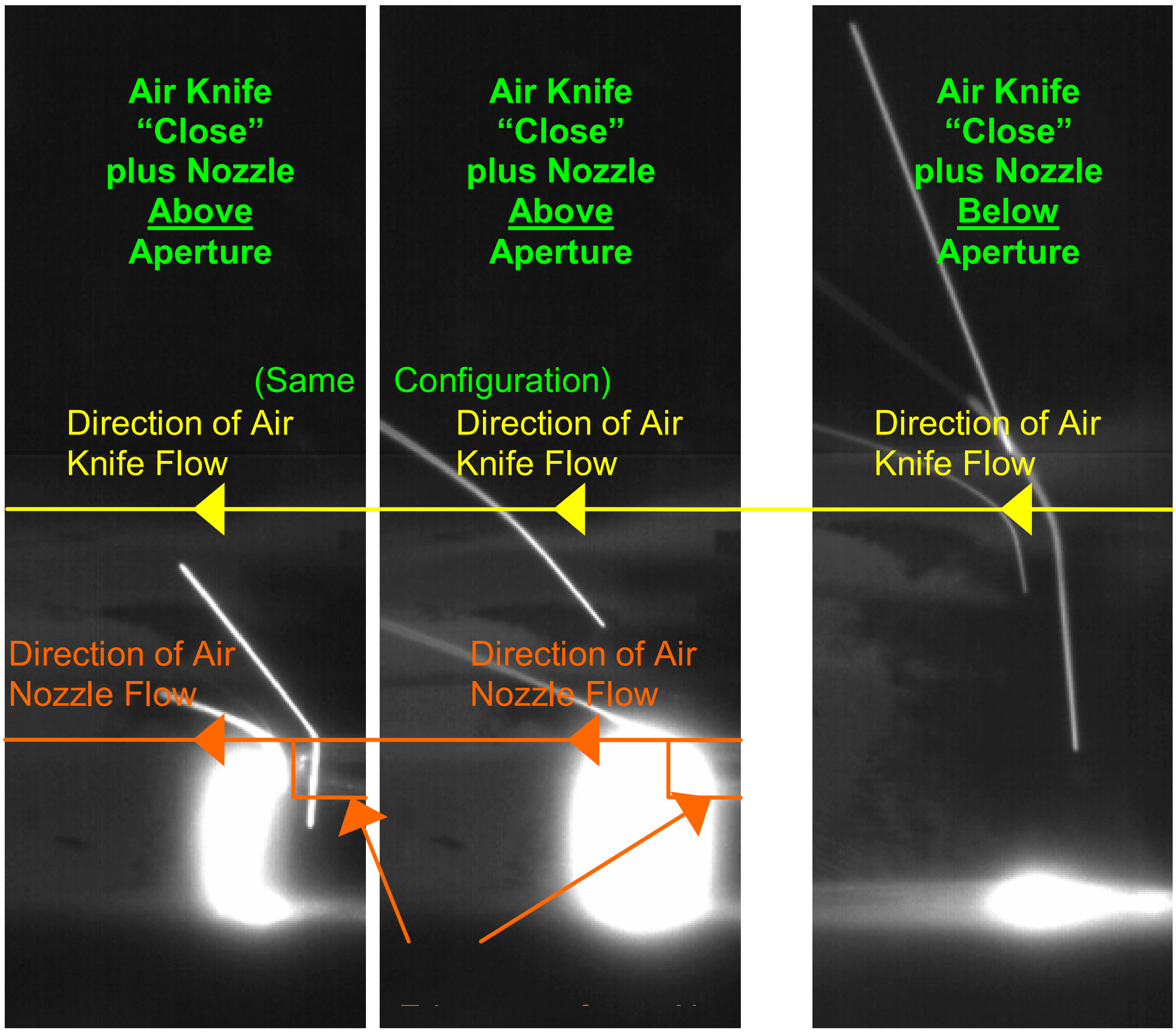


Figure **52**. Air knife in combination with air nozzle above versus below aperture (Camera Aperture: 2.8, Exposure time: 1/1002 sec., framerate: 600fps).

Based on the motion of spatter in individual frames of the high speed video and the exposure time of each frame the spatter travelling above the aperture has an estimated velocity of 25 m/sec.

Gas Flow Management

Another important factor to consider in gas flow design is the management of the gas flow caused by the gas and air knives, jets, and nozzles. A high velocity gas jet creates a pressure drop which causes the surrounding air to flow toward the gas jet as displayed in Figure **53**.

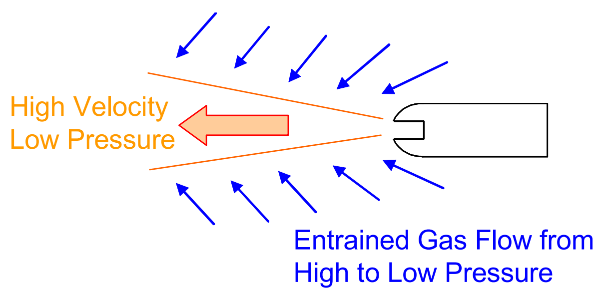


Figure **53**. Gas flow induced by pressure drop at high velocity gas jet.

During welding experiments the pressure drop caused by the high velocity air nozzle above the aperture was large enough to draw a significant volume of air through the aperture hole as shown in Figure **54**.

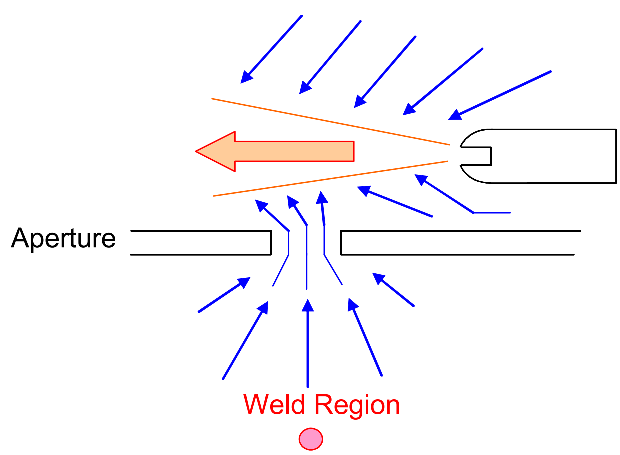


Figure **54**. Gas flow near weld region with single aperture.

A string can be placed near the region of interest in order to roughly gauge the gas flow and turbulence in the region. This simple string test was used to verify that there was indeed disturbance in the air around the weld region. This disturbance affected the GMAW shield gas, necessarily located below the aperture hole, with a resultant negative impact on weld quality and increase in surface porosity.

The solution to this problem was to use two apertures. The pressure drop created by the air nozzle pulled air through the upper aperture hole. However, the lower aperture, with a smaller aperture hole, limited the air drawn upward from the weld region. Instead, most of the air traveling through the upper aperture hole was drawn from between the two apertures, as shown in Figure **55**. This prevented disturbance of the gases in the weld region and maintained weld quality.

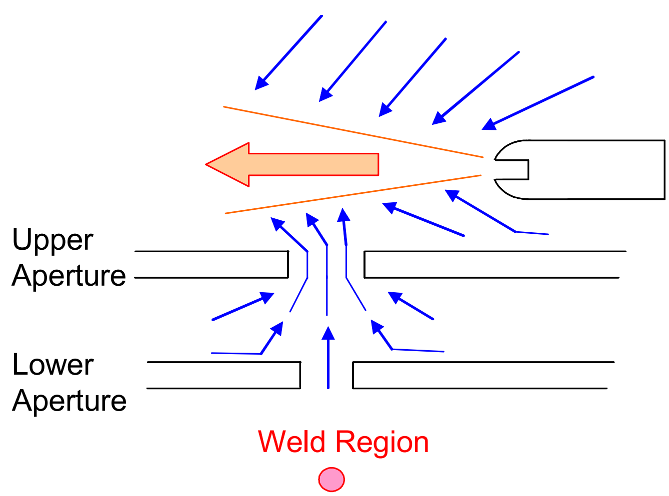


Figure **55**. Gas flow near weld region with both an upper and lower aperture.

It is also important to make sure that the high velocity gas or air jets used for plasma suppression or spatter control are not deflected by any object in its path back into the GMA weld region. This requires ensuring that the jet is aimed high enough above the aperture hole so that no air is deflected downward by the edge of the aperture hole, and also aiming the jet away from any other objects which could deflect it down toward the weld region. For example, when the air knife assembly was installed on the hybrid welding system at ARL Penn State for the initial pipe welding experiments, the high velocity air jets deflected off of the rotary positioner which

disrupted the flow of shield gases in the weld region, as shown in configuration A in Figure **56**. The dark blue arrows represent the air flow from the air nozzles and the light blue arrows represent the flow deflected by the rotary positioner. The obvious solution was to aim the air knife assembly in the opposite direction, away from the rotary positioner as shown in configuration B.

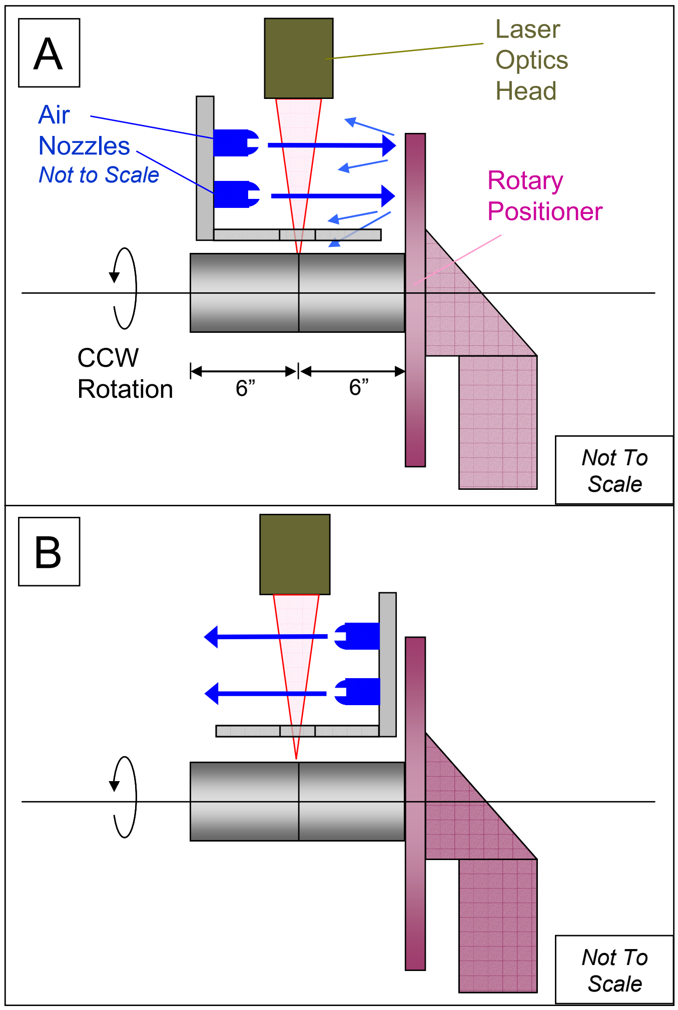


Figure **56**. Gas flow management during pipe welding at ARL Penn State.

However, when the pipe welding system was installed at GD NASSCO shipyard and production pipe assemblies were welded, a different gas deflection issue was encountered. The high velocity gas jet was deflected by elbow joints, as shown in configuration C in Figure **57**, such that shield gas flow in the weld region was again disrupted. Due to the position of the seam

tracking camera being immediately ahead of the laser, and the laser begin ahead of the GMAW torch relative to the weld travel direction (and also relative to the view given in the figure) the air knife assembly could only be aimed parallel to the pipe axis toward or away from the rotary positioner (corresponding to right and left in the figure). Fortunately, the straight pipe sections used in production welds at NASSCO shipyard were significantly longer, >600 mm (2 feet), than the 150 mm (6 inch) sections used during parameter development at ARL Penn State, which allowed more room to direct the high velocity air jet so as to not be deflected by the rotary positioner. The solution was to replace the lower air nozzle with a ServoRobot air knife which incorporated an aperture with an upward angled lip. The air jet closely follows the aperture and angled tip, and was successfully directed upward, above the rotary positioner, as shown in configuration D.

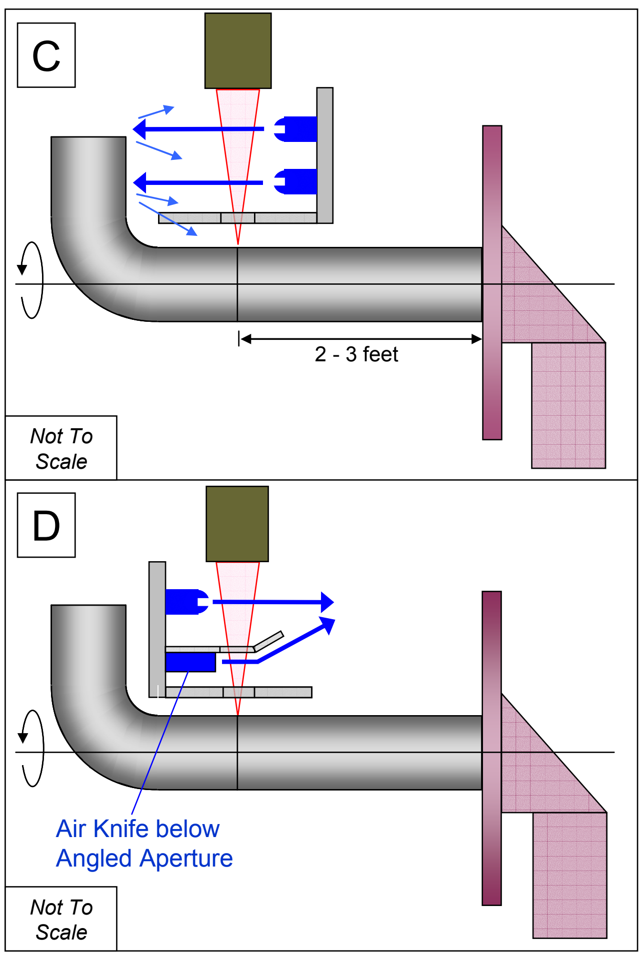


Figure **57**. Gas flow management during pipe welding at GD NASSCO shipyard.

The final air knife design, shown in Figure **58**, took into account all of the factors previously discussed and the lessons learned while welding at Penn State ARL and NASSCO shipyard. This design features a simple gas nozzle aimed perpendicular to the laser beam just above the weld region using argon gas to suppress the plasma and gas plumes and slightly deflect spatter. An air knife and two air nozzles are employed above the apertures for spatter control. The air from the air knife is directed upward by the lower of two angled apertures and thus does result in disturbance to the GMAW shield gas. The aperture below the air knife was sufficient to ensure that the air flow did not disrupt the laser shield gas near the weld region and was effective in stopping the upward motion of most of the spatter. Above the air knife high velocity air nozzles from ExAir Corporation were used for additional spatter control needed to deflect the spatter traveling at the highest velocities. They were placed side by side to cover the full width of the possible trajectory of spatter traveling upward through the aperture holes of the three apertures. The significant air flow caused by the high velocity air jets from these nozzles was directed by the three apertures such that shield gases in the weld region were not disrupted. For the same reason the nozzles were placed above the air knife to give a greater distance between the nozzles and the weld region.

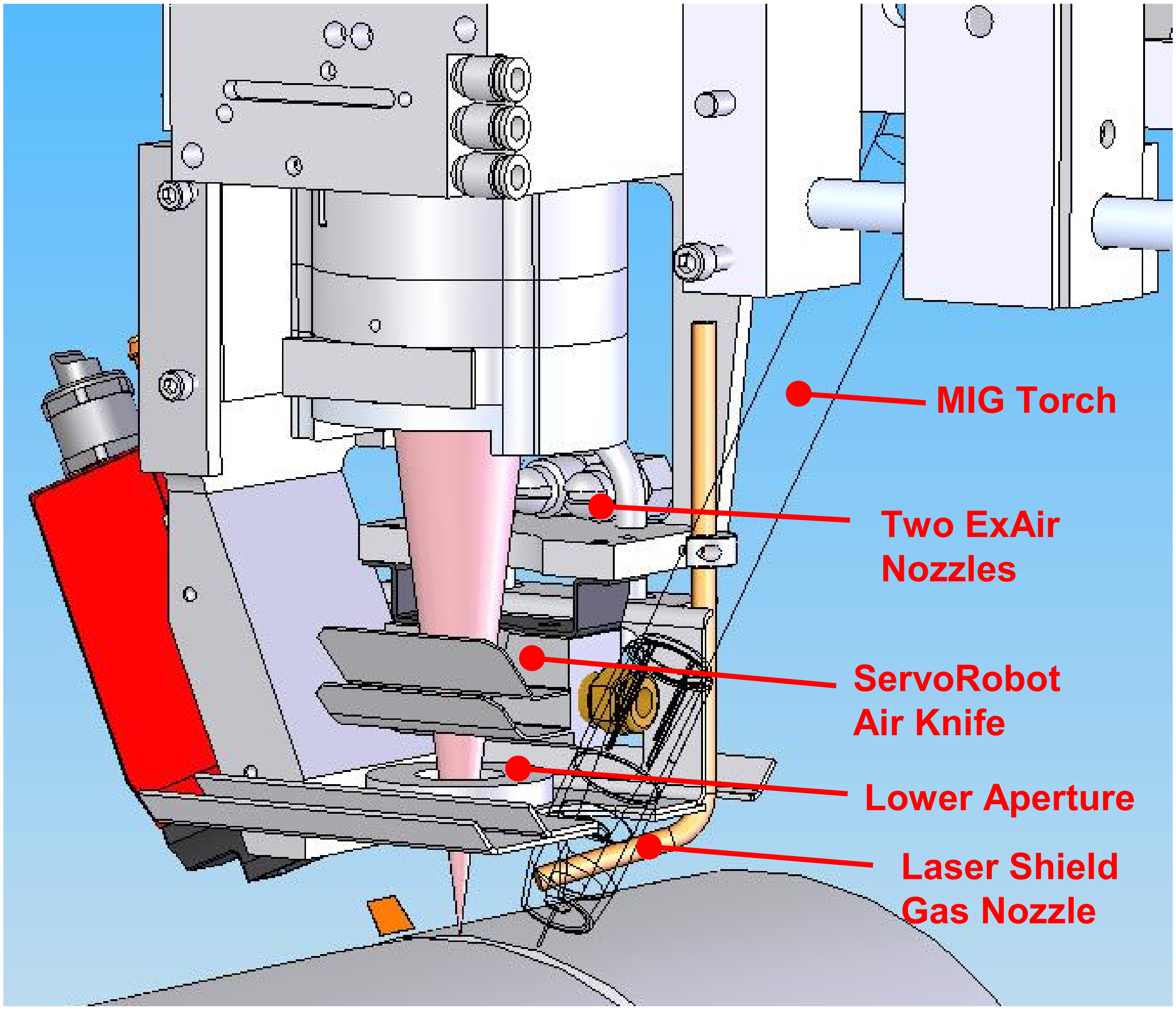


Figure **58**. Final gas management system design.

Wall Thickness Variations and Edge Preparation

Laser welding with optimal penetration characteristics and rootside reinforcement geometry is very sensitive to variations in wall thickness. If the process is optimized for a given wall thickness and the thickness increases, lack of penetration may result. If the thickness decreases, the vapor keyhole may fully penetrate leading to material expulsion at the root. Unfortunately, existing ASTM A53 specifications for pipe and ASME B16.9 specifications for fittings allow for substantial variations in wall thickness. As such, it was determined early on that machining of pipe edges, both inside and outside diameter might be necessary. This would serve to ensure a

constant land height, and hence volume of material, for the laser to melt and penetrate. Figure **59** illustrates the potential joint mismatch that can result using pipes that actually meet the specifications, and how edge preparation can ensure that a constant joint geometry is presented to the laser beam. Though additional expense for machining is required to ensure consistent joint geometry (unless suppliers can provide materials with tighter tolerances), the edge preparation is believed to be necessary to guarantee consistent weld quality.

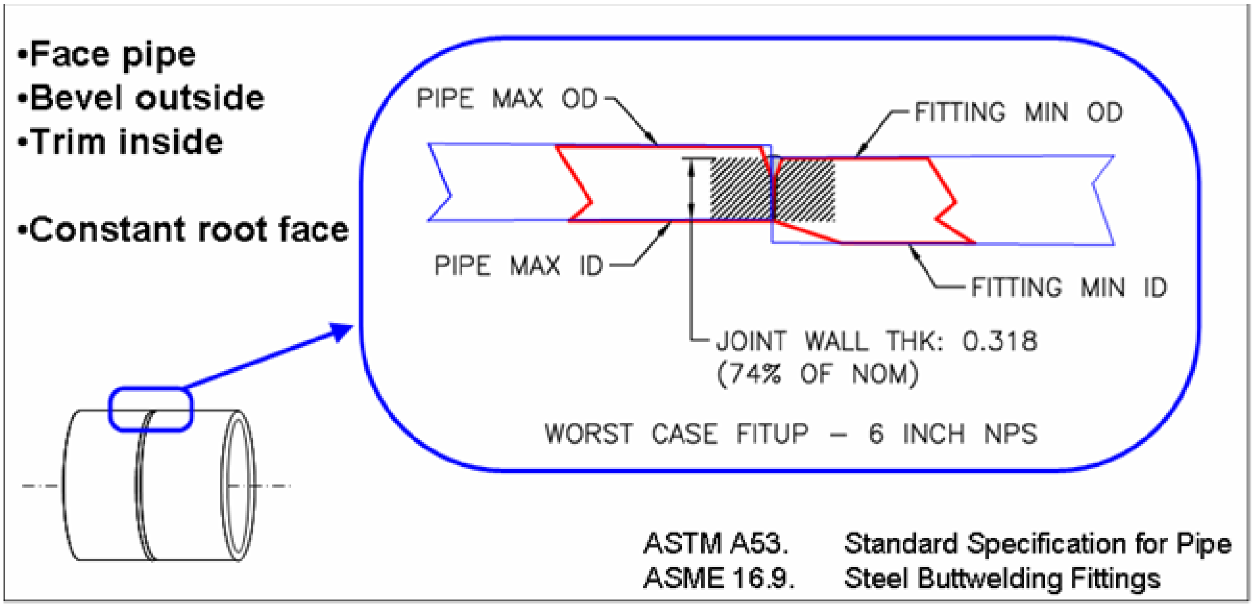


Figure **59**. Illustration of potential wall thickness variations, and how machining of edges can ensure a consistent joint presentation to the laser beam.

Fortunately, several manufacturers supply portable tools for that can provide the required edge preparation for pipes and elbows. Figure **60** shows one such tool. Regrettably, however, it was determined that the elbow mandrels, which would work fine if merely facing and machining the outside diameter of elbows, do not work when machining of the inside diameter is required. The standard position of the mandrel within the elbow would cause interference with the inside diameter tool bit, so the mandrel must be extend further into the elbow. This, in turn, results in misalignment with the center of the pipe opening, and unacceptable edge machining. This is illustrated in Figure **61** and Figure **62**. Though modules that allow the tool bits to track the inside diameter are available, and would indeed provide a consistent land height, there is

potential for eccentricity of pipe and fittings to result in unacceptable mismatch. As such, for all work conducted on NASSCO production spools, all fittings were prepared in a machine shop.

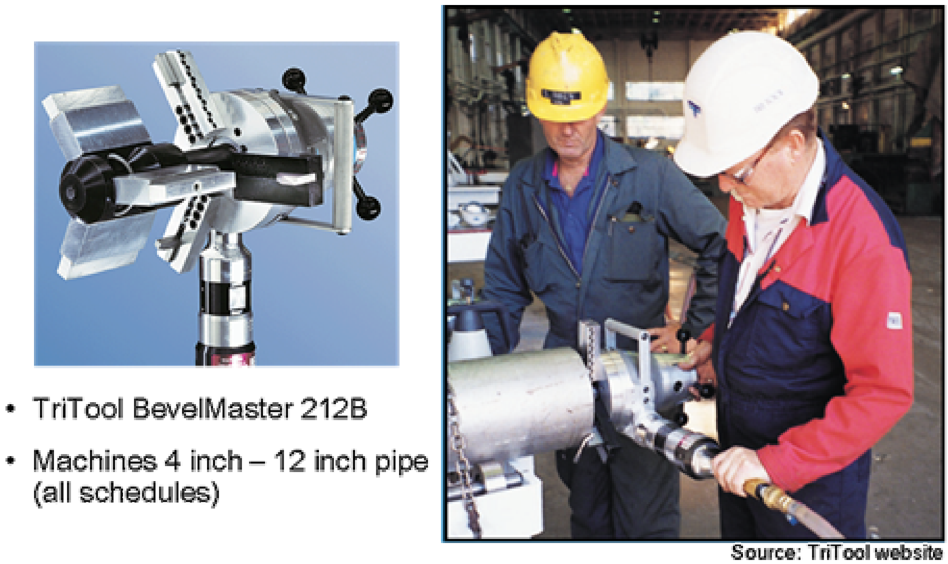


Figure **60**. Example of portable pipe edge bevelling machine (source: TriTool website).

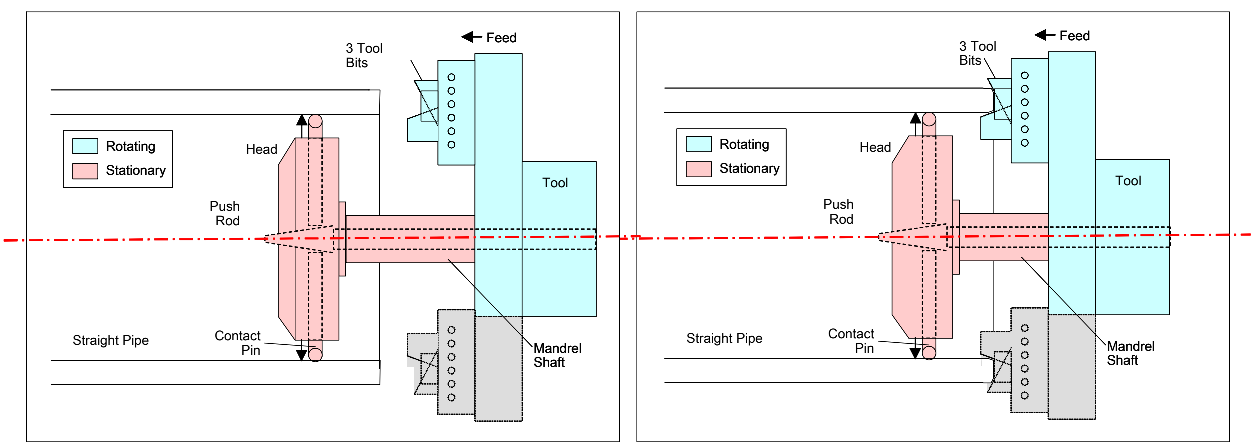


Figure **61**. Illustration of operation of pipe edge bevelling machine. Shown are the tool fixtured in the pipe (left), then moved into machining position, where is faces the pipe, bevel the outside diameter, and trims the inside diameter (right).

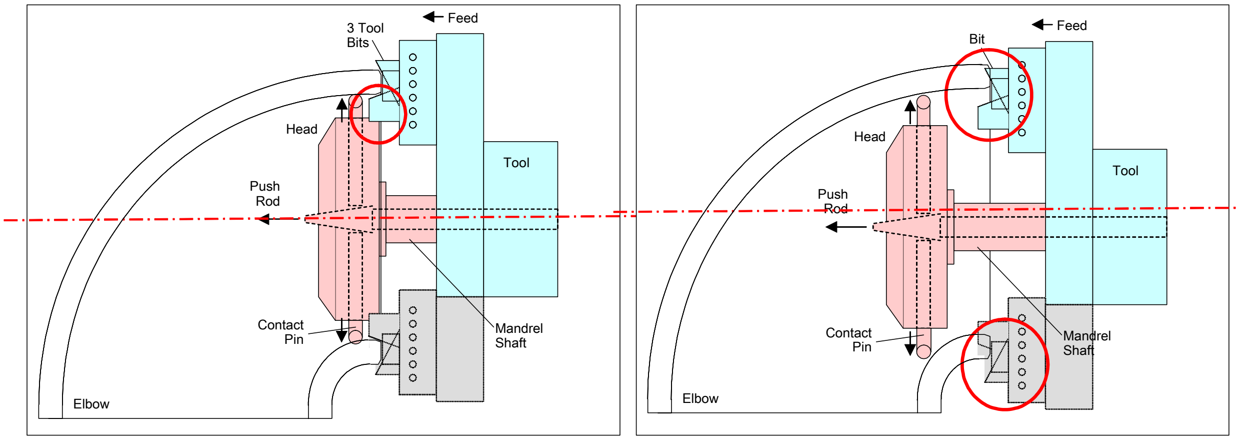


Figure **62**. Illustration of problems encountered when applying the edge beveling machine to fittings. Shown in interference between the tool bit and the fixture (left), and misalignment of the tool bits (right).

Another item of note related to edge preparation is that standard fittings come with a pre-machined beveled edge, the length of which is account for in design of pipe spools. In order to provide the required joint geometry and land height, this bevel must be machined off, thus reducing the length of the fitting by a non-negligible amount. This must be compensated for either by using sliding collars or fittings downstream of the machined fitting or by lengthening pipe sections are required. If the production volume is high enough, it is likely that it would be economically viable for suppliers to provide fittings that have the required dimensional tolerance, thus eliminating the need for pre-weld machining operations.

SHIPYARD INSTALLATION

Hybrid Weld Parameters

Though the preliminary investigations conducted at ARL Penn State with both the 4.5 kW Nd:YAG laser and the 7 kW fiber laser provided a strong basis for development of process parameters over the entire range pipe diameters and wall thicknesses, additional parameter development was still required. In the end, processing conditions were determined which satisfied the requirements for approval for a wide range of pipe diameters and wall thicknesses — they passed visual tests, radiographic tests, face and root bend tests, and tensile tests. It is important to realize, though, that they may not have been optimized for speed or weld quality.

Through experimentation is was determined that only two edge preparations were required to permit welding with the available equipment. For wall thickness less than 0.375 inch, straight butt joints were sufficient, though knocking the edge off with a file was necessary to ensure robust seam tracking. Some tests conducted using saw-cut edges were successful, but to ensure success the majority of tests employed machined edges. For wall thickness greater than 0.375 inch, a bevel was required to allow the 7 kW laser to achieve full penetration with a robust and repeatable process. These joint preparations are shown below in Figure 63 and Figure 64. Note that it is believed that use of a higher power laser may enable full penetration of straight butt joints up to 0.500 inch wall thickness (data from 12 kW fiber lasers hybrid welds from the Bremer Insitut für Angewande Strahltechnik in Bremen, Germany supports this). If true, saw-cut edges may be sufficient to produce suitable welds, and could thus eliminate the need for machined edges. Further investigation is certainly required, but significant additional cost savings may be realized.

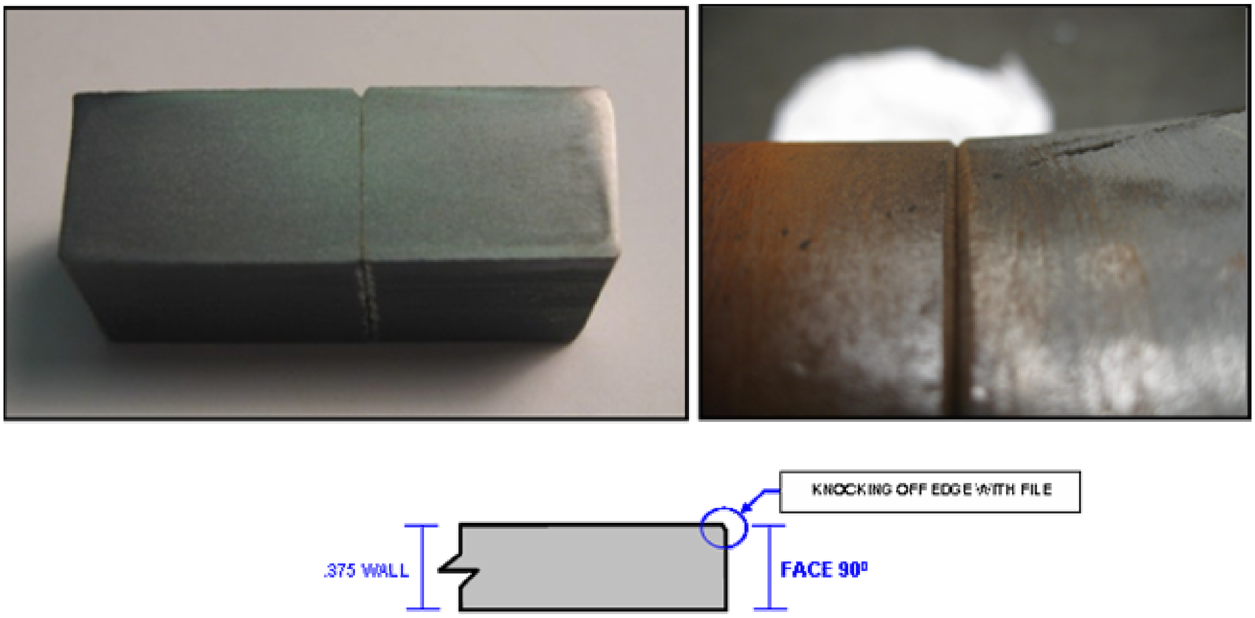


Figure **63**. Joint preparation for joints with less than 0.375 inch wall thickness.

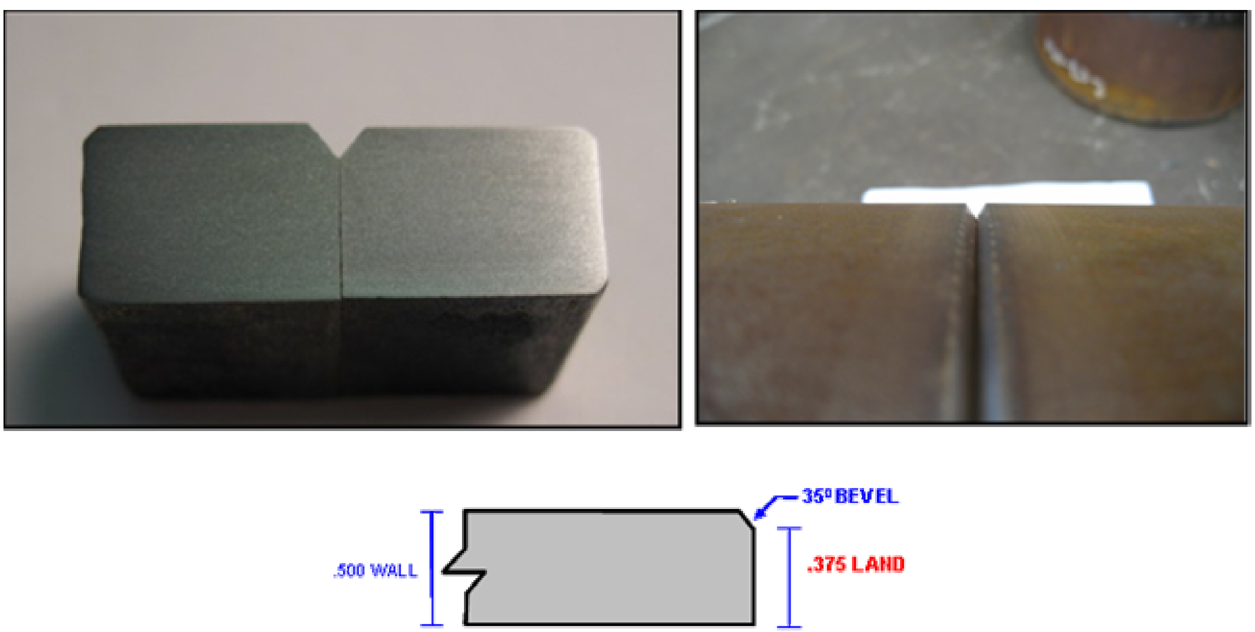


Figure **64**. Joint preparation for joints with 0.500 inch wall thickness.

As mentioned above, it is likely that a higher power laser would eliminate the need to bevel thicker sections, provided that the thickness can be maintained within some limit. Though pipe

thickness tend to remain fairly constant, wall thickness on fittings varies dramatically and is cause for concern. If possible, fitting suppliers that can provide pre-machined fittings and/or keep tighter tolerance on wall thickness variation and eccentricity would allow the hybrid pipe welding technology to operate to its greatest potential benefit.

Though experiments were carried out to investigate the ability of the hybrid welding process to weld through conventional tack welds, in the end it was decided to produce all tack welds as autogenous GTA welds, i.e. without added filler wire. This eliminated any possible problems caused by the need for the laser to penetrate additional filler material supplied through the tack welding process. Figure 65 illustrates the difference in joint preparation between the standard bevel and tack weld, and the hybrid bevel and tack weld. Note the fact that the hybrid joints require a tight fit-up actually makes it somewhat easier for the pipe fitter, since a predefined gap does not need to be carefully maintained during fit-up.

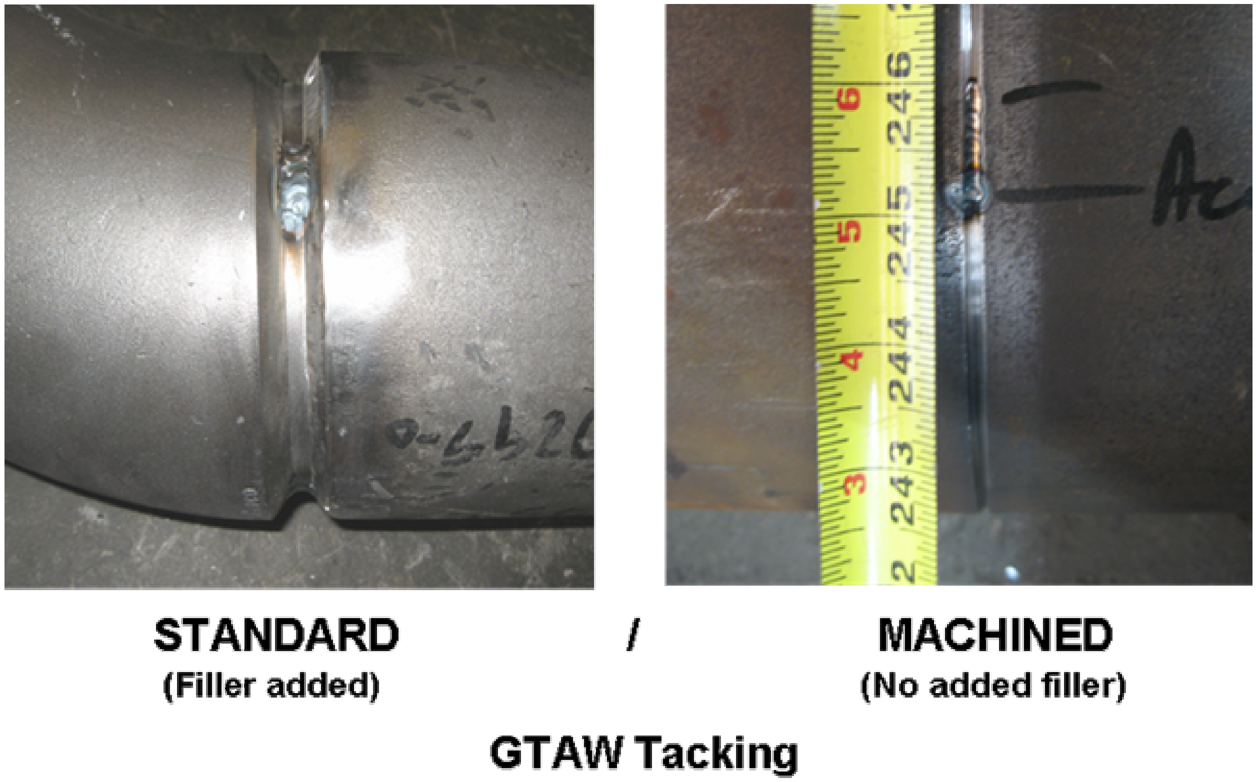


Figure **65**. Comparison of joint preparation and tack welding for conventional and hybrid prepared joints.

More than 500 welds were conducted at NASSCO to help define parameters over the broad range of pipe diameters and wall thicknesses used in the shipyard, and to ensure a robust and repeatable process. The parameters that were eventually used for qualification of pipe up to 16 inch diameter are tabulated in

Table 2. Figure 66 shows characteristic macro cross sections of the welds that were produced at NASSCO.

Table 2. Processing for various pipe sizes subjected to qualification testing.

PIPES SIZES AND PARAMETERS

Pipe size	Sch.	Wall size	Land / Bevel	Butt	Laser	Weld Speed	Spacing between Laser & Wire	W.F.S
4"	40	0.237	0.237	MACH	4.5	30	25mm / Off set 35	250
4"	80	0.337	0.337	MACH	6.5	40	25mm / Off set 35	250
6"	40	0.281	0.281	MACH	4.5	30	25mm / Off set 35	250
6"	80	0.432	0.432	MACH	6.5	20	25mm / Off set 35	200
8"	40	0.322	0.322	MACH	6.5	40	25mm / Off set 35	250
8"	80	0.5	.375 / 60	MACH	7	25	25mm / Off set 45	350
10"	40	0.365	0.365	MACH	6.5	25	25mm / Off set 35	200
10"	XS	0.5	.375 / 45	MACH	7	20	25mm / Off set 45	400
12"	40	0.375	0.375	MACH	6.5	25	25mm / Off set 50	250
12"	XS	0.5	.375 / 35	MACH	6.5	20	25mm / Off set 45	350
14"	40	0.375	0.375	MACH	6.5	25	25mm / Off set 45	250
16"	40	0.375	0.375	MACH	6.5	25	25mm / Off set 35	250
16"	XS	0.5	0.375 / 35	MACH	6.5	25	25mm / Off set 45	400
18"	40	0.375	0.375	MACH	6.5	35	25mm / Off set 35	350
18"	XS	0.5	.375 / 35				PENDING	

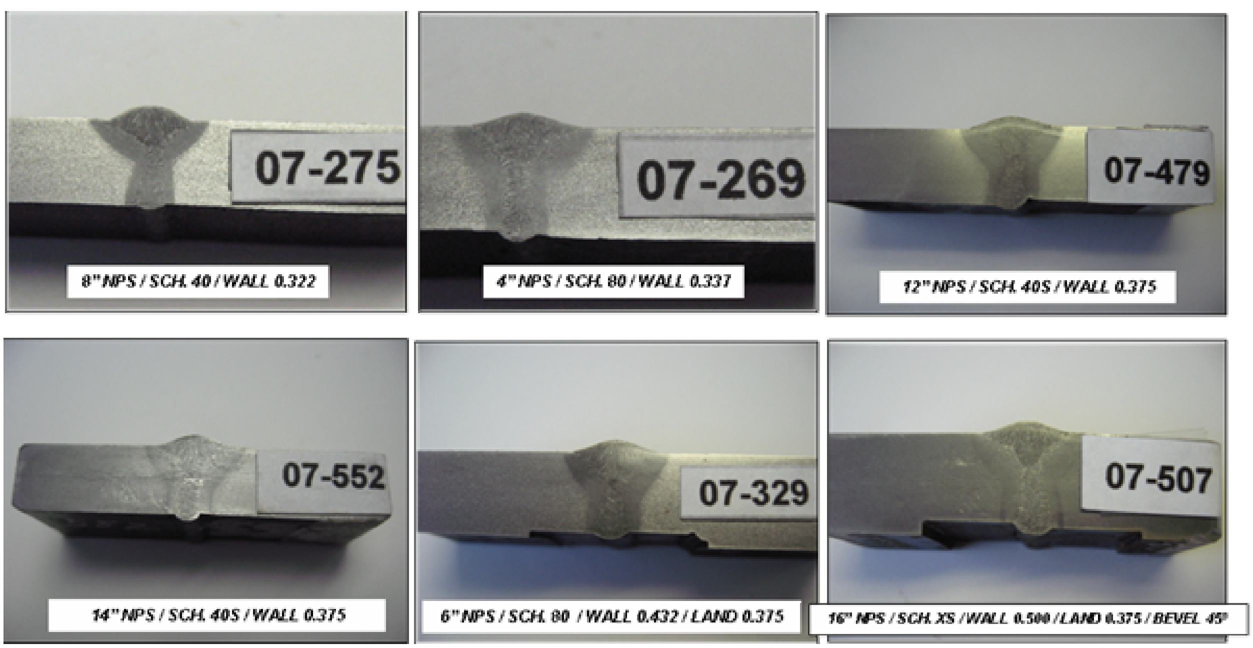


Figure **66**. Macro cross sections of hybrid pipe welds produced at NASSCO shipyard.

Test Production Run

Once hybrid laser-GMA parameters were developed to produce visually acceptable welds on a set of pipe schedules that covered the range of wall thicknesses, a small test production run was conducted to provide an initial view into potential production rate. In order to mimic the random order of pipe spools that come through a welding cell in the course of a normal day, the pipes were presented in a pseudo-random order so that the operator was required to re-teach the location of each joint prior to executing the weld. A photograph of the ten welded pipes is provided in Figure 67, and the results of the time study are presented in Table 3.

The time to load, teach, and weld 10 joints averages under seven minutes per weld. This substantial improvement over conventional techniques can be attributed to the ease in utilizing the system due to simple user interface and the automatic seam tracking, as well as to the substantial improvement in weld time due to the higher travel speeds and reduced number of weld passes realized with the hybrid welding process.

Figure **67**. Photograph of pipes joined with a hybrid laser-GMA weld for the small production test run time study.

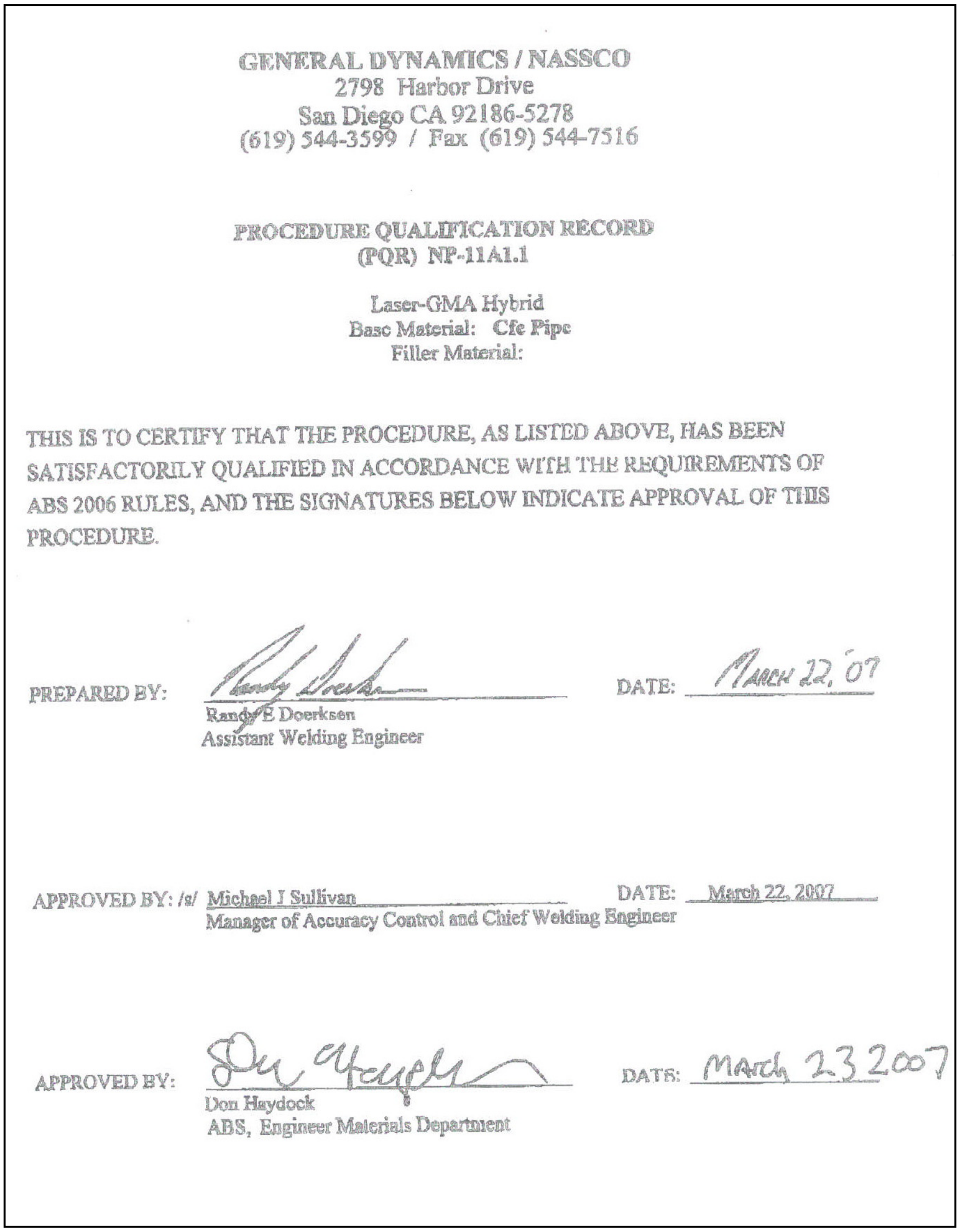
Table **3**. Results of the time study.

Pipe Diameter {inch}	Pipe Schedule	Load {min:sec:}	Teach Joint {min:sec:}	Weld {min:sec:}
4	40	00:32	05:25	06:35
6	40	11:05	14:15	16:05
4	80	18:30	22:55	24:00
8	40	25:25	29:55	30:35
8	80	33:15	36:55	38:35
4	40	39:50	42:40	44:20
6	40	46:10	49:35	50:55
6	80	52:10	55:10	57:10
8	40	58:00	61:10	62:35
8	80	64:00	67:05	68:40
Total				68 m 40 s

Not addressed in this initial investigation was the comparison of pipe preparation time. At the time of this test, only machined pipe edges had been utilized, straight butts for thinner wall pipes and special bevels for thicker wall pipes. Portable pipe edge preparation tools were available to perform these machining operations. After this test, as parameters were developed for an expanded range of pipe diameters and wall thicknesses, saw-cut edges were sometimes used for the thinner wall pipe with acceptable results. As development moved into joining of pipe to fittings, we found that the pipe edge preparation tool was not effective, due to interference and misalignment. As such, many of the fittings were diverted to the NASSCO machine shop for edge preparation. This obviously resulted in increase logistical burden and cost. For this reason, a separate effort was undertaken to determine in fitting suppliers would be willing to provide pre-machined fittings at a cost-effective price. This is discussed further in the Cost Benefit Analysis section of the report.

Approved Welds

The first ABS approval of hybrid welding in the U.S. was received on pieces produced by NASSCO operators during training at ARL Penn State in February 2007. The signed Procedure Qualification Record cover sheet is shown in Figure 68.



GENERAL DYNAMICS / NASSCO
2798 Harbor Drive
San Diego CA 92186-5278
(619) 544-3599 / Fax (619) 544-7516

PROCEDURE QUALIFICATION RECORD
(PQR) NP-11A1.1

Laser-GMA Hybrid
Base Material: Cfe Pipe
Filler Material:

THIS IS TO CERTIFY THAT THE PROCEDURE, AS LISTED ABOVE, HAS BEEN SATISFACTORILY QUALIFIED IN ACCORDANCE WITH THE REQUIREMENTS OF ABS 2006 RULES, AND THE SIGNATURES BELOW INDICATE APPROVAL OF THIS PROCEDURE.

PREPARED BY: Randy E Doerksen, Assistant Welding Engineer — DATE: March 22, 07

APPROVED BY: /s/ Michael J Sullivan, Manager of Accuracy Control and Chief Welding Engineer — DATE: March 22, 2007

APPROVED BY: Don Haydock, ABS, Engineer Materials Department — DATE: March 23 2007

Figure **68**. Signed ABS approval of hybrid pipe weld.

The data Table 4 in shows the pipe schedules that have been approved for hybrid welding as of August 2007. Approval for pipe schedules up to 30 inch in diameter are pending.

Table 4. Table of joints with ABS approval and with approval pending (produced in Aug 2007).

Pipe size	Sch.	Wall size	Land / Bevel	ABS Approved	X-Ray	Bend	Test No.
4”	40	0.237	0.237 / 0	*PENDING*	Passed	Passed	07-213
4”	80	0.337	0.337 / 0	*PENDING*	Passed	Passed	07-270
6”	40	0.280	0.280 / 0	*(PQR) YES*	Passed	Passed	03-09
6”	80	0.432	0.432 / 0	*PENDING*	Passed	Passed	07-302
8”	40	0.322	0.322 / 0	*PENDING*	Passed	Passed	07-274
8”	80	0.500	0.375 / 60	*PENDING*	Passed	Passed	07-311
10”	40	0.365	0.365 / 0	*PENDING*	Passed	Passed	07-265
10”	XS	0.500	0.375 / 45	*PENDING*	Passed	Passed	07-424
12”	40	0.375	0.375 / 0	*PENDING*	Passed	Passed	07-478
14”	40	0.375	0.375 / 0	*PENDING*	Passed	Passed	07-553
16”	XS	0.500	0.375 / 45	*PENDING*	Passed	Passed	07-510

Sources of Weld Failures at the Shipyard

Throughout the course of the demonstration period at NASSCO, numerous factors resulted in failed welds. It may be instructive for those engaged in similar projects to review these, as many may be correctable.

- Land/root face mismatched
  - more consistency in edge preparation may help
- Land length/root face variations
  - more consistency in edge preparation may help
- Tracking focal point shifting
  - improved head design may eliminate shifting of the tracking system relative to the location of the laser spot
  - alternatively, a better means of calibrating and adjusting the location of the seam tracker may help
- Cracking tack welds
  - because autogenous tack welds were used, they do not have the strength of conventional GTAW tack welds
  - a modification of the program to allow laser tack welds in order to boost the strength of the tacked joint prior to full welding may be a simple fix
- Surface too shiny to track
  - a diffuse reflection of the seam tracking laser is necessary to robust tracking

    - there is a tendency for operators to believe a shinier joint preparation is better, when in many cases, the surface should rather be roughened with sand paper or a grinding wheel in order to track correctly
- Closed valves from process gases and air
    - system should alert operator of gas flow problems.
- Water supervision fault (GMAW power supply anti-freeze)
    - the water cooled GMAW power supply sprung a leak
- Wrong joint tracking template entered
    - operator error
- Short radius elbows, pipe length limits (23 inch or 584 mm)
    - this refers to interference with the hybrid welding head or robot during rotation
    - a modified head design would help mitigate this problem
- Variances in wall thickness on elbows and reducers
    - more consistency from fitting suppliers would help
- Pipe lengths Limits (6 feet or 1883 mm)
    - a larger system base would eliminate this problem
- Some joints, particular on larger pipes have slight gaps
    - it is possible to use seam tracking data to modify process parameters in real time
    - it is believed more desirable to ensure consistent gap through machining if possible
- Pendant cord being damaged / fragile pendent (used for every weld)
    - the robot pendant was dropped and broken twice, expensive and time consuming
    - a more durable pendant and protected pendant cord are necessary since the pendant is required for every weld

COST BENEFIT ANALYSIS

To help evaluate the potential cost benefit, an analysis of actual joining time of production pipe spools joined using the hybrid pipe welding system was compared to the time normally allotted to complete each spool using conventional joining techniques. Each spool is different, and the details of each are included in Appendix C. Since the number of joints required for each spool, or actually welded for each spool, varies from one to three, the times were normalized for two joints per spool. The times include everything from edge preparation, to grind, fit-up, and tack welding, to set-up and welding, to weld repair when required.

Of note is that during these trials, fittings had to be sent to the machine shop to prepare the edge. This time is included in the analysis. However, conversations with Allied Supply Company reveal that fittings may be purchased pre-machined to the required geometry. If the system were to proceed to full production, it would likely be of benefit to pay the premium required for pre-machined fittings in order to reduce the production time and logistical burden in the shipyard. The information received from the fitting supplier is shown below.

CURRENT PRICE
Price for standard fittings that are not machined

- 4" STD 90 ELL $16.32
- 6" STD 90 ELL $22.60
- 8" STD 90 ELL $67.03
- 10" STD 90 ELL $118.39
- 12" STD 90 ELL $167.60

PRICE FOR MACHINED FITTINGS:
There would be a one time tooling fee of $600.00 per size. Prices are for fitting and machining. Based on a quantity of 20 for each size.

- 4" STD 90 ELL $34.28
- 6" STD 90 ELL $46.49

Based on the costs provided for pre-machined fittings of 4 inch and 6 inch diameters, it is possible to extrapolate the cost for up to 12 inch diameter. Two extrapolation methods were used, providing a range of costs. These costs are presented in Figure 69. These values are used in the final costs analysis.

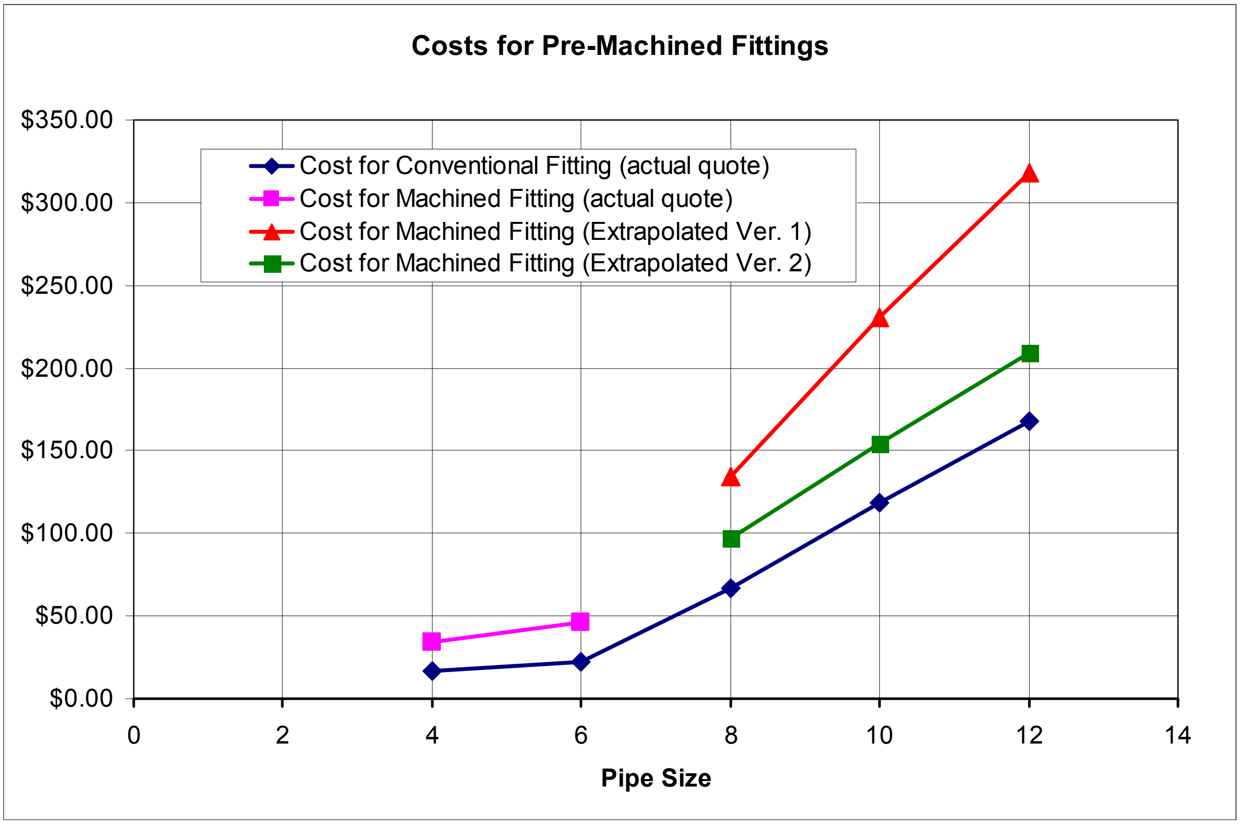


Figure 69. Costs for pre-machined fittings.

The comparison of conventional joining time to joining time using the hybrid pipe welding system has been constructed to provide both actual total time including machining of fittings, and an estimate of time if pre-machined fittings were used. The assumptions are stated below, and the comparison is shown in Figure 70, with data tabulated in Table 5.

Assumptions:

- Normalize to 2 joints.
    - If reducer, then split time evenly between the two joints and multiply by 2
    - If only one side could be welded but both ends were prepped, then cut prep time in half, then multiply by 2
    - If 3 joints were welded, than divide by 3 and multiply by 2
- Since prep time includes machining of pipes and fittings, for calculating "Hybrid w/o machine time" assume 25% of total time was for machining the pipe and 75% was for machining the fitting. This can be used to look at time savings if premachined fittings are purchased.

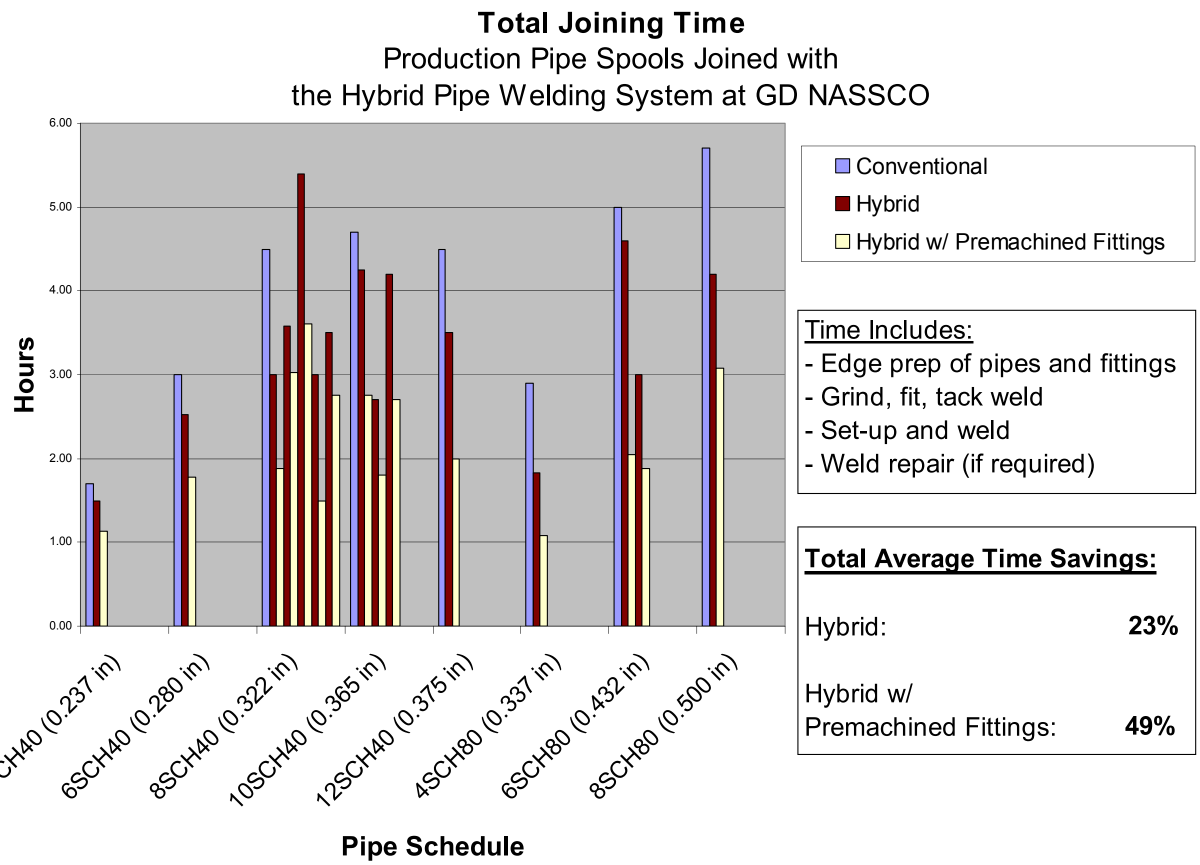


Figure 70. Total joining time for conventional joining methods compared to hybrid pipe welding.

Table 5. Time study comparing the actual hybrid welding process to conventional joining process for actual production pipe spools.

		Prep Edge of pipe and fitting	Grind, Fit, Tack	Set-Up & Weld	Weld Repairs	No. Joints (to be used as multiplier)	**Total (includes a multiplier to normalize to two joints)**	Hours Saved	% Diff from Conv.	Production Pipe No.
4SCH40	Conventional	0.50	0.30	1.00	0.00		**1.80**			
0.237 inch	Hybrid	0.50	0.50	0.25	0.25	2	**1.50**	0.30	17%	1
	Hybrid w/o machine time						**1.13**	0.68	38%	
6SCH40	Conventional	1.00	0.50	1.50	0.00		**3.00**			
0.280 inch	Hybrid	1.50	1.20	0.75	0.33	3	**2.52**	0.48	16%	7
	Hybrid w/o machine time						**1.77**	1.23	41%	
8SCH40	Conventional	1.00	1.50	2.00	0.00		**4.50**			
0.322 inch	Hybrid	1.30	1.00	0.30	0.00	2	**2.60**	1.90	42%	3
	Hybrid w/o machine time						**1.63**	2.88	64%	
8SCH40	Conventional	1.00	1.50	2.00	0.00		**4.50**			
0.322 inch	Hybrid	0.38	0.75	0.50	0.17	1	**3.58**	0.92	20%	6
	Hybrid w/o machine time						**3.02**	1.48	33%	
8SCH40	Conventional	1.00	1.50	2.00	0.00		**4.50**			
0.322 inch	Hybrid	1.20	0.50	0.50	0.50	1	**5.40**	-0.90	-20%	10
	Hybrid w/o machine time						**3.60**	0.90	20%	
8SCH40	Conventional	1.00	1.50	2.00	0.00		**4.50**			
0.322 inch	Hybrid	2.00	0.50	0.50	0.00	2	**3.00**	1.50	33%	11
	Hybrid w/o machine time						**1.50**	3.00	67%	
8SCH40	Conventional	1.00	1.50	2.00	0.00		**4.50**			
0.322 inch	Hybrid	1.00	1.00	0.50	1.00	2	**3.50**	1.00	22%	14
	Hybrid w/o machine time						**2.75**	1.75	39%	
10SCH40	Conventional	1.00	1.50	2.20	0.00		**4.70**			
0.365 inch	Hybrid	2.00	1.00	0.50	0.75	2	**4.25**	0.45	10%	4
	Hybrid w/o machine time						**2.75**	1.95	41%	
10SCH40	Conventional	1.00	1.50	2.20	0.00		**4.70**			
0.365 inch	Hybrid	1.20	0.50	0.50	0.50	2	**2.70**	2.00	43%	10
	Hybrid w/o machine time						**1.80**	2.90	62%	
10SCH40	Conventional	1.00	1.50	2.20	0.00		**4.70**			
0.365 inch	Hybrid	2.00	1.00	0.50	0.70	2	**4.20**	0.50	11%	13
	Hybrid w/o machine time						**2.70**	2.00	43%	
12SCH40	Conventional	1.50	1.70	3.00	0.00		**6.20**			
0.375 inch	Hybrid	2.00	1.00	0.50	0.00	2	**3.50**	2.70	44%	9
	Hybrid w/o machine time						**2.00**	4.20	68%	
16SCH40	Conventional	1.50	2.00	3.50	0.00		**7.00**			
0.375 inch	Hybrid	1.50	0.70	0.50	0.50	1	**6.40**	0.60	9%	16
	Hybrid w/o machine time						**4.15**	2.85	41%	
4SCH80	Conventional	1.00	1.10	1.30	0.00		**3.40**			
0.337 inch	Hybrid	1.00	0.50	0.33	0.00	2	**1.83**	1.57	46%	2
	Hybrid w/o machine time						**1.08**	2.32	68%	
6SCH80	Conventional	1.00	1.10	1.90	0.00		**4.00**			
0.432 inch	Hybrid	3.40	0.50	0.50	0.20	2	**4.60**	-0.60	-15%	8
	Hybrid w/o machine time						**2.05**	1.95	49%	
6SCH80	Conventional	1.50	1.60	1.90	0.00		**5.00**			
0.432 inch	Hybrid	1.50	1.00	0.50	0.00	2	**3.00**	2.00	40%	15
	Hybrid w/o machine time						**1.88**	3.13	63%	
8SCH80	Conventional	1.10	1.20	2.60	0.00		**4.90**			
0.500 inch	Hybrid	1.50	1.00	0.50	1.20	2	**4.20**	0.70	14%	5
	Hybrid w/o machine time						**3.08**	1.83	37%	
10SCH80	Conventional	1.10	1.40	2.80	0.00		**5.30**			
0.500 inch	Hybrid	4.00	0.50	0.50	1.00	1	**12.00**	-6.70	-126%	12
	Hybrid w/o machine time						**6.00**	-0.70	-13%	
12SCH80	Conventional	1.20	1.50	3.20	0.00		**5.90**			
0.500 inch	Hybrid	4.00	0.50	0.50	1.00	1	**12.00**	-6.10	-103%	12
	Hybrid w/o machine time						**6.00**	-0.10	-2%	

With all preparation of fittings and pipe performed at NASSCO, and including any possible repair time, the recorded total time savings average 23%. If pre-machined fittings are utilized, it is estimated that total joining time would drop to 49% savings. It is believed that further development and use of the system would gradually eliminate the need to make repairs, which would further reduce this time. Additionally, use of a higher power laser would eliminate the need to bevel the edge of thick walled pipes and fittings, thus resulting in additional savings.

According to a 2005 NSRP SP-7 Laser Pipe Welding Technology study performed at NASSCO shipyard, over an 11 week period the pipe shop joined an average of 416 joints per week, spending an average of 918 hours per week in joining operations. If this is extrapolated to a year, more than 47,000 man hours are spent on pipe [4]. Though not all pipe spools can be accommodated with the current design, it is safe to assume that a redesign would permit joining of the vast majority. If the system (or more than one system) were utilized to full capacity with all machining performed at NASSCO, the savings would be 23% of 47,000 hrs or 10,810 hrs per year. If pre-machined fittings were to be utilized, the savings can be estimated to increase to 23,030 hrs per year. If burdened labor costs are estimated at $100/hr and average cost for premium charged for purchase of a pre-machined fitting is $25 per joint, then annual savings can be estimated at $1.78M. As mentioned, these savings may increase as the process becomes more robust and the need for weld repair diminishes.

It is worth noting that, though only one hybrid pipe welding system currently exists, for relatively low cost it would be possible to procure additional robotic pipe welding systems. The fiber laser technology would permit use of a beam switch that would enable one laser system to service multiple workcells in a timesharing configuration. Since the laser cost is the most substantial portion of the investment ($700k to $1M, depending on laser power), this would mean the incremental cost for bringing additional workcells online would be substantially less than the initial investment for the first one. Additionally, it may be possible to feed the laser to other areas of the shipyard for cutting of plate and pipe, and welding on the panel line, where hybrid welding has recently been shown to result in dramatically reduced distortion in thin plate [9]. Ongoing work sponsored by Navy ManTech through the Institute for Manufacturing and Sustainment Technology (IMAST) and the Center for Naval Shipbuilding Technology

(CNST) is addressing the implementation and qualification issues associated with these alternate hybrid laser applications.

LESSONS LEARNED / SUGGESTIONS FOR IMPROVEMENT

Numerous lessons were learned about how to effectively implement new and complex technology into a shipyard, the most important of which are listed below.

- Involve shipyard upper management, safety personnel, production management, and welders early on to build strong buy-in.
- Develop strong shipyard commitment to provide labor, equipment, parts, and monetary support beyond the direct project allotment when required.
- Select top people at the shipyard to participate at all levels. They should possess a high degree of motivation, self-confidence, and strong working relationship with others around the yard. This was invaluable in getting overall acceptance of the system as it was installed in the pipe shop.
- Include budget for safety training, robot training, and system training of shipyard personnel.

Additional lessons learned about the technology itself, in addition to those outlined in the experiment discussions, are listed below.

- Air knife design and gas management are of critical importance. This is discussed in more detail elsewhere in this report.
- Varying land height, especially noticeable using standard elbows can result in poor welds, so edge preparation may be necessary. The effectiveness of edge preparation tools with machining of elbows is discussed elsewhere in this report.
- Optical quality of the cover glass affects cover glass lifetime, i.e. higher optical quality cover glasses last longer.
- Welding ahead of Top Dead Center (TDC) can be used to provide a smoother and more stable bead profile than welding at TDC.
- If too much process energy is used, i.e. too low travel speed or too high power, the weld can penetrate through the back and result in less backside reinforcement and small spatter on pipe ID. Consequences for porosity were not investigated. This is discussed in the Phase III Experimental section of this report.
- Smaller land height seems to provide a more stable process, though this must be weighed against ability to provide enough wire feed speed to fill large bevels at desired travel speeds for thicker wall pipe.
- Ability to vary the overlap (tie-in) parameters is necessary to ensure an acceptable tie-in (not too much material, not too much heat and blow through).

- Separating the laser from GMAW torch can lead to easier determination of processing parameters, though has inability to deal with gaps or add special filler metal alloys if necessary (not necessary for pipe welding).
- Tracking is necessary, even for carefully machined and fitted pipe.
- Simple user interface and ease of use is critical. The Wolf Robotics system offers the ability for operator to teach a single point (at proper orientation) and system uses this information along with information about pipe diameter to calculate entire path. Though not exact, it is typically close enough for seam tracker to provide required path corrections (seam tracker has +/- 30 mm travel).
- Interface should have ability to log all essential variables.

Suggestions for improvement in the next generation system are listed below.

- Add laser tack welding option.
- Add automatic joint-find (including orientation-find for offset-angled pipes). Assume operator only needs to get the robot near the correct orientation and near the joint (say 3 inches away). May require seam tracker software modifications.
- Include a more robust and industrially hardened robot teach pendant.
- Improve head design with caliper-type adjustments to set relative orientation of GMAW torch to laser to ServoRobot camera.
- Develop simple calibration procedures and/or tools for orienting GMAW torch to laser to ServoRobot camera.
- Develop simple calibration procedures for ServoRobot joint tracking offsets (perhaps to include an improved alignment laser that clearly shows when focus is on the top of the pipe).
- Improve head design for (a) improved access to elbows and flanges, and (b) improved access reach, especially with larger "Weld Offset" settings.
- Incorporate improved air knife designs into new head.
- Add video camera and flat panel monitor for operator to observe process. Perhaps two: one to allow operator to check tracking during WELD BLOCKED dry runs, and another filtered one to allow operator to observe the weld as he would during manual parameter development, i.e. as if looking through a weld mask (the vast weld experience of these operators could really help in parameter development, but they can't see the weld from outside the cell).
- Include a manual slide to enable robot motion perpendicular to chuck motion. Incorporate a motorized elevator for the rotary chuck (note this may require use of a robot servo axis to maintain calibration).
- Consider changing chuck design to reduce instances of interference with robot or hybrid head.

- Add an ability to teach two (or more) joints at once. This could allow an operator to teach all welds in a pipe spool at once, thus eliminating need to repeat the entire procedure for each individual joint on the spool.
- Improved cable/hose management, reduce radiuses, reduce length of GMAW cable if possible.
- Add button on the Wolf Cell Controller to block weld and remove "Dry Run" option.
- Incorporate longer jaws on the chuck to support larger pipe spools.
- In the head design, add a plate or brush to block laser plasma or arc light from ServoRobot camera. On several occasions, the reflection for the arc or plasma reflected off the pipe and interfered with the seam tracker.
- The system could be made easier to use and more flexible in operation if certain aspects of the seam tracking were easily communicated to the Wolf Cell Controller.
- Provide more training for NASSCO welders on operation of the seam tracker and the GMAW power supply.
- Include gas monitors for air knives and other gases to alert operator when gas is out or wasn't turned on. In several cases, failed welds were caused by gas problems that weren't immediately discovered.
- Contact suppliers to provide pre-machined fittings to meet the joint geometry and tolerance requirements. Having an ability to pull the required fitting off the shelf rather than schedule machine shop time would result in significant savings in cost, time, and effort.

ACCOMPLISHMENTS

- First qualification of hybrid laser welding by the American Bureau of Shipping in the U.S.
- First demonstration of hybrid laser welding in a U.S. shipyard.
- First production components hybrid welded in a U.S. shipyard.
- First hybrid welded components installed on a U.S. ship.
- Basis of hybrid pipe welding system specified by ARL Penn State and produced by Wolf Robotics was used for another similar system later ordered by Caterpillar. Transition of portions oft technology developed during the program to U.S. industry.

A list of presentations and publications provided by the project team during this program follows:

Apr 2005	SP-7 Welding Technologies Panel Meeting	Project Update - Sullivan	Myrtle Beach, SC (Presentation)
May 2005	American Society of Materials (ASM) Trends in Welding Conference	Reutzel, Kelly, Martukanitz, Bugarewicz, Michaleris, "Laser-GMA Hybrid Welding: Processing Monitoring and Thermal Modeling"	Pine Mountain, GA (Presentation & Conference Proceedings)
Jun 2005	*American Welding Society (AWS)* Charting the Course in Welding: U.S. Shipyards Conference	Reutzel, Sullivan, Mikesic, Martukanitz, "Joining of Pipe with Lasers: Weld Test Results and Cost Analysis"	Williamsburg, VA (Invited Presentation)
Sept 2005	SP-7 Welding Technologies Panel Meeting	Project Update – Reutzel	Portland, ME (Presentation)
Oct 2005	International Congress on Lasers and Electro-Optics (ICALEO) Conference	Reutzel, Kelly, Tressler, Martukanitz, "Experimental Analysis of Practical Aspects of Hybrid Welding of Thick Sections"	Miami, FL (Presentation & Conference Proceedings)
Jan 2006	Technology Meeting with General Dynamics Electric Boat personnel	Project Update – Reutzel	State College, PA
Apr 2006	SP-7 Welding Technologies Panel Meeting	Project Update - Sullivan	Provo, UT (Presentation)
Jun 2006	American Welding Society (AWS) *Welding Journal*	Reutzel, Sullivan, Mikesic, "Joining Pipe with the Hybrid Laser-GMAW Process: Weld Test Results and Cost Analysis"	(Invited Journal Article)
Jun 2006	Fabricators and Manufactures Association (FMA) Practical Welding Today	Interviewed for article "Hybrid Laser-Arc Welding Research Underway" - Reutzel	(Interview)

Aug 2006	SP-7 Welding Technologies Panel Meeting	Project Update – Reutzel ARL Penn State organized discussion of Hybrid Weld qualification with shipyards, NJC, NSWC-CD, and SEA 05M.	Carderock, MD (Presentation and Discussion)
Oct 2006	International Congress on Lasers and Electro-Optics (ICALEO) Conference	Reutzel, Kern, Tressler, "Continued Experimental Analysis of Practical Aspects of Hybrid Welding of Thick Sections"	Scottsdale, AZ (Presentation & Conference Proceedings)
Feb 2007	Demonstration with Open Invitation to U.S. Shipyards	Demonstration of Hybrid Pipe Welding System - Reutzel	State College, PA (Presentation & Demonstration)
Mar 2007	SP-7 Welding Technologies Panel Meeting	Project Update – Sullivan	Fort Collins, CO (Presentation and Discussion)
Aug 2007	SP-7 Welding Technologies Panel Meeting	Project Update – Sullivan Shipyard Demonstration	San Diego, CA (Presentation and Demonstrations)
Oct 2007	International Congress on Lasers and Electro-Optics (ICALEO) Conference	Reutzel, Kern, Tressler, Sullivan, "Experience with Shipyard Installation of a Hybrid Pipe Welding System"	Orlando, FL (Presentation & Conference Proceedings)
Nov 2007	*Society for Naval Architects and Marine Engineers (SNAME)* Maritime Technology Conference and Expo and Ship Production Symposium	Reutzel, Kelly, Sullivan, Huang, Kvidahl, Martukanitz, "Hybrid Laser-GMA Welding for Improved Affordability"	Ft. Lauderdale, FL (Presentation and Conference Proceedings)

CONCLUSIONS

The combination of laser with conventional gas metal arc welding technology offers substantial increases in production rate of joining pipe through single-pass joining compared to multi-pass conventional techniques. The hybrid process has been examined and developed for this application, and the process has been qualified through the American Bureau of Shipping for a wide range of pipe schedules. A system to realize this application has been specified, designed, built, and implemented in General Dynamics NASSCO Shipyard, and been subjected to a 7 month evaluation on the production floor. Lessons learned have been documented to benefit future efforts.

Even considering additional time spent to achieve proper fit-up, the estimated savings are substantial, and range from 23% to 49% time savings based on data collected on actual production pipe spools. With upwards of 47,000 hours per year spent in joining pipe per year, the potential cost savings are substantial. Additional process improvements would certainly be realized as the technology matures and would result in additional savings. Reductions in filler wire consumption and the attendant reductions in hazardous weld fume emissions would also be substantial.

ACKNOWLEDGEMENTS

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BIBLIOGRAPHY

[1] Steen, W.M. and Eboo, M. (1979) Arc augmented laser welding, *Constr. III* (7), pp.332-336.

[2] Steen, W.M. (1980) Arc augmented laser processing of materials, *J.Appl.Phys.*, Vol.51, No.11, pp.5636-5641.

[3] Kelly, S. M., Martukanitz, R.P., Michaleris, P., Bugarewicz, M., Huang, T.D., and Kvidahl, L., "Low heat input welding for thin steel fabrication" *J. Ship Prod.* 22 (2), 105 (2006).

[4] Reutzel, E.W., Mikesic, D.A., Tressler, J.F., Crue, R.A., Gwinn, E.A. and Sullivan, M.J. (2005) Laser Pipe Welding: Technology Evaluation and Cost Analysis, ARL Penn State Technical Report No. 04-014, Feb 2005 (available at www.nsrp.org).

[5] Reutzel, E.W., Kelly, S.M., Tressler, J.F., and Martukanitz, R.P. (2005) Experimental analysis of practical aspects of hybrid welding of thick sections, *Proceedings of the International Congress on Laser and Electro-Optics (ICALEO 2005)*, LIA, Miami, FL, USA, Paper No. 306, 10 pages.

[6] Reutzel, E.W., Kern, L.A. and Tressler, J.F. (2006) Continued experimental analysis of practical aspects of hybrid welding of thick sections, *Proceedings of the International Congress on Laser and Electro-Optics (ICALEO 2006)*, LIA, Scottsdale, AZ, USA, Paper No. 1906, 9 pages.

[7] Reutzel, E.W., Kern, L.A. and Tressler, J.F., Sullivan, M.J. (2007) Experience with shipyard installation of a hybrid pipe welding system, *Proceedings of the International Congress on Laser and Electro-Optics (ICALEO 2007)*, LIA, Orlando, FL, USA, Paper No. 1904, 10 pages.

[8] Reutzel, E.W., Kelly, S.M., Sullivan, M.J., Huang, T.D., Kvidahl, L., Martukanitz, R.P. (2007) Hybrid laser-GMA welding for improved affordability, *Proceedings of the SNAME Maritime Technology Conference and Expo and Ship Production Symposium*, Fort Lauderdale, FL, USA, 11 pages.

[9] Kelly, S.M., Reutzel, E.W., Martukanitz, R.P. (2007) Hybrid Laser-Arc Welding Process Development and Performance, *Proceedings of the International Congress on Laser and Electro-Optics (ICALEO 2007)*, LIA, Orlando, FL, USA, Paper No. 607.

APPENDIX A. System Specification

PERFORMANCE SPECIFICATION

Laser-GMA Hybrid Pipe Welding Demonstration System

Prepared By:

Applied Research Laboratory, Penn State University (ARL Penn State)

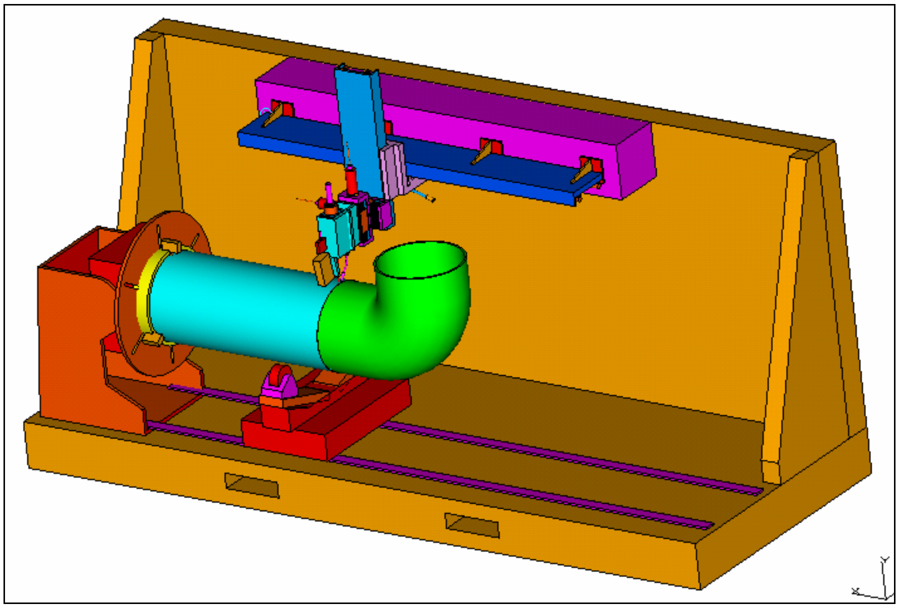
National Steel and Shipbuilding Company (NASSCO)

For:

Center for Naval Shipbuilding Technology Program (CNST)

— (Rev. 1.1) —

25 August 2005



Possible System Configuration

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1. Laser-GMA Hybrid Pipe Welding Workcell

1.1. Introduction

This document sets the performance specifications for a pipe welding workcell utilizing the hybrid laser arc welding (HLAW) process. The HLAW process combines the laser beam welding (LBW) process with the gas metal arc welding (GMAW) process (see Figure 1). This enables single-pass welding of material that requires 3 to 5 passes using conventional processes (see Figure 2). This will enable welding time savings of up to 80% or more, predicted to result in an increase in throughput, less heat input, reduced residual stress and distortion, improved process quality, and substantial cost savings.

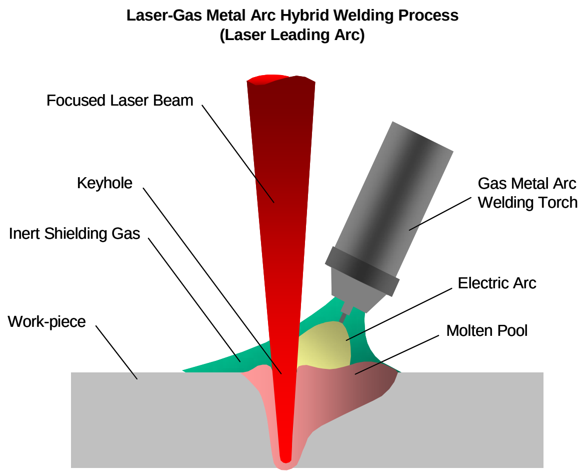

Figure 1. Schematic of Hybrid Laser Arc Welding (HLAW).

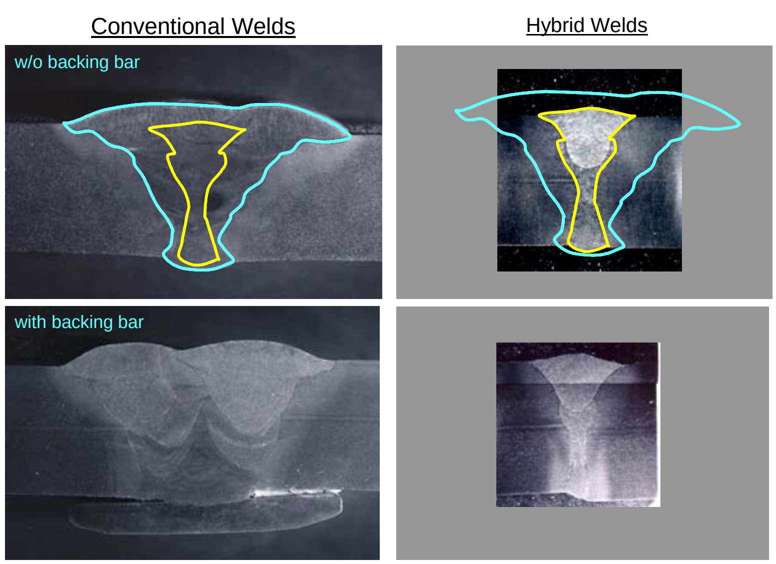

Figure 2. Comparison of Conventional vs. Hybrid welds for ~12.7 mm (1/2 inch) thick material.

This demonstration system will be used to develop, improve, and qualify hybrid pipe welding processes and systems. The system will be initially located at ARL Penn State for debugging, process development and qualification test preparations. In September 2006, the system will be moved to the pipe shop at National Steel and Shipbuilding Company (NASSCO) in San Diego, CA for benchmarking, demonstrations, and evaluation in a production environment. ARL Penn State is responsible for technical project management and process development.

This workcell is to be used for joining carbon steel pipe (ASTM A-53 / A-53M, ASTM A-106) to buttweld fittings (ASME B16.9). The diameter of pipe to be welded ranges from 4 inch NPS to 30 inch NPS, in wall thicknesses up to 12.7 mm (½ inch).

1.2. Workcell Overview

The workcell components that must be integrated to realize this system are broken into a base system and two options. A Laser with Chiller, to be provided by ARL Penn State, is an assumed component of the system (7 kW IPG Photonics fiber laser), and is therefore not listed. The so-called Base Laser-GMA Hybrid Pipe Welding Workcell consists of the following major components:

a. Integrated Joint Tracking System
b. Weld Head Manipulation System
c. Rotary Positioner
d. Workcell Pendant
e. Workcell Control System / Programming Station (with safety system in accordance with ANSI Z-36)
f. Base / Support Structure
g. Safety Enclosure (with safety interlocks in accordance with ANSI Z-36, with suitable exhaust collection and filtration, and with process viewing via safety windows and/or video systems)

Additional quotes are requested for the following two options:

Option A[1]. In addition to the base system, supply:

h. HLAW Head
i. GMAW Power Supply And Wire Feeder

If Option A is not executed, a suitable HLAW Head and GMAW Power Supply and Wire Feeder will be mutually agreed upon and integrated into the system, but they will be purchased by ARL Penn State.

---

[1] ARL/Penn State to purchase separately if option is not exercised

Option B[2]. In addition to the base system, supply:

j. Workcell Safety Enclosure (with signage and safety interlocks in accordance with ANSI Z-36, with suitable exhaust collection and filtration, and with process viewing via safety windows and/or video systems)

Note that a parallel effort is slated to provide a temporary safety shelter at NASSCO. If the WorkCell Safety Enclosure is not executed as an option, the shelter may be appropriately outfitted with suitable safety accessories.

Each major component is discussed in detail herein. All other equipment should rely on commercially-available off-the-shelf (COTS) technology wherever possible.

One potential configuration for the workcell is shown in Figure 3.

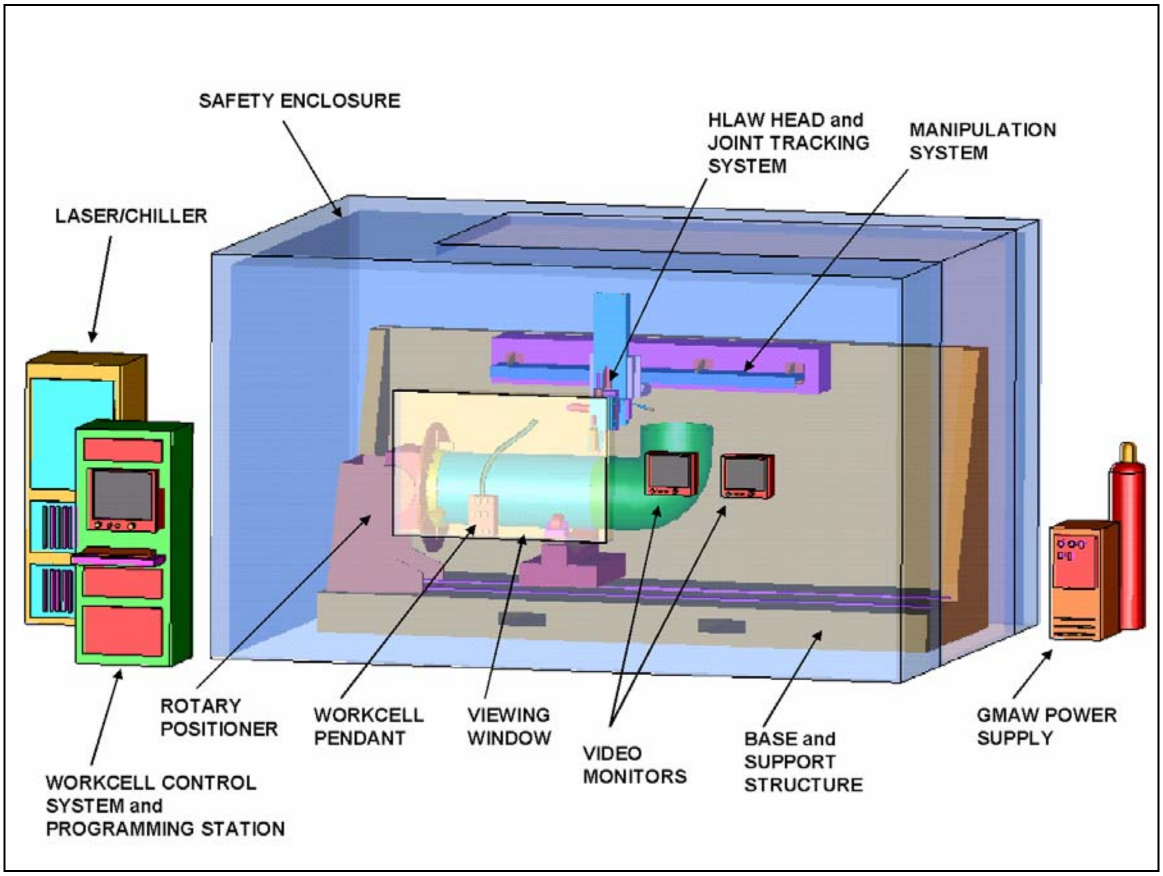

Figure 3. Potential workcell configuration (for illustrative purposes only).

[2] NASSCO / ARL Penn State to build enclosure on site if option is not exercised

1.3. Process Flow

The high level process flow as seen from the perspective of the operator is illustrated in Figure 4.

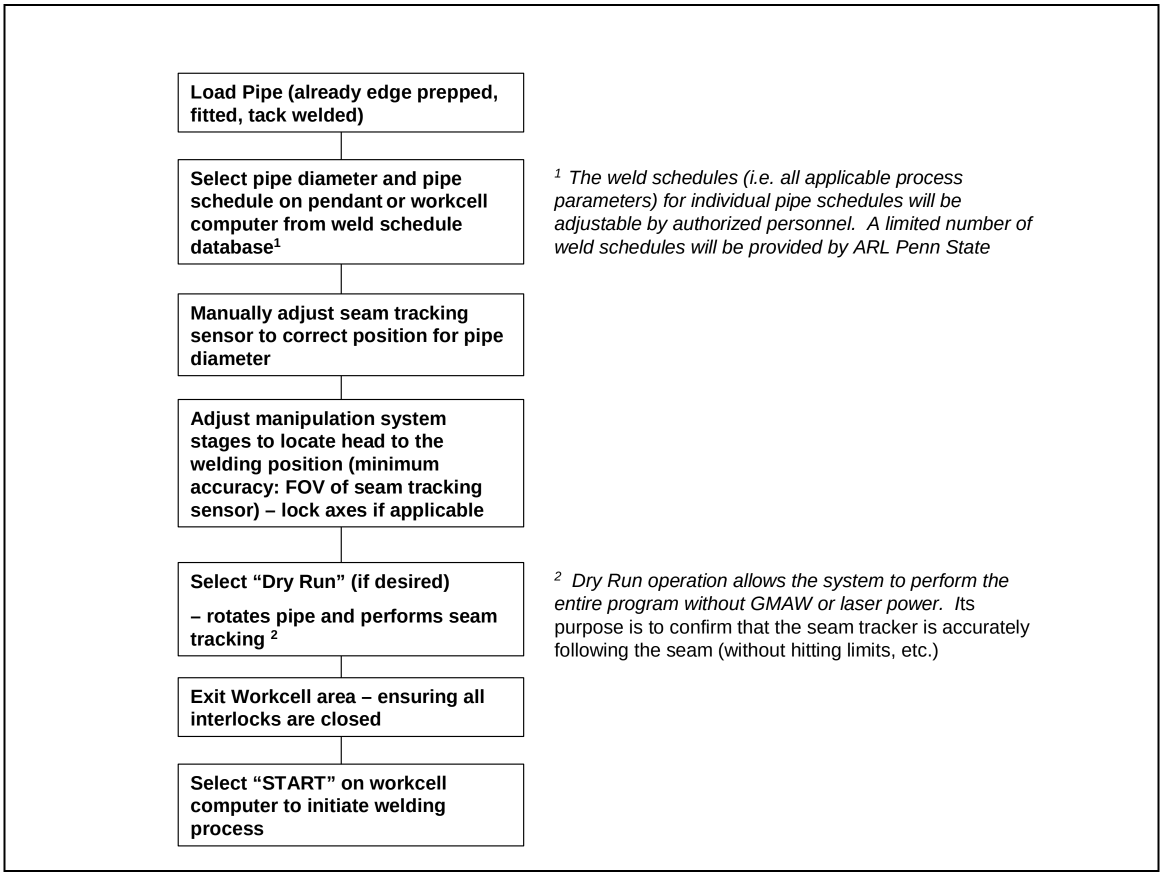

Figure 4. High Level Operational Flow Chart[3]

Note that it is assumed that pipe edges can be prepared to edge quality sufficient for HLAW using commercial off-the-shelf joint edge preparation equipment to enable NASSCO personnel to fit-up and tack weld to the quality specified herein. Discussions with pipe edge preparation equipment manufacturers indicates that this is possible.

Note that in the final demonstration system, it is envisioned that the operator will only be required to select the pipe diameter and schedule, but the software should also permit authorized personnel to add/edit/delete records from the weld schedule database (password protected). For the demonstration system, ARL Penn State will provide the required weld schedules for the required wall thicknesses. Also note that due to geometrical requirements, the joint tracking system sensor must be adjustable to accommodate the broad range of pipe diameters—this is discussed in detail in Section 3.

[3] Note that system should be able to operate both with and without the Joint Tracking System activated.

The flow chart in Figure 5 illustrates the detailed process flow that is automatically executed by the Workcell Control System once the operator hits the "START" button. It also discusses the various parameters that must be "programmed" into the weld schedule database for each pipe diameter and schedule. The process data will be developed and provided by ARL Penn State or other qualified personnel.

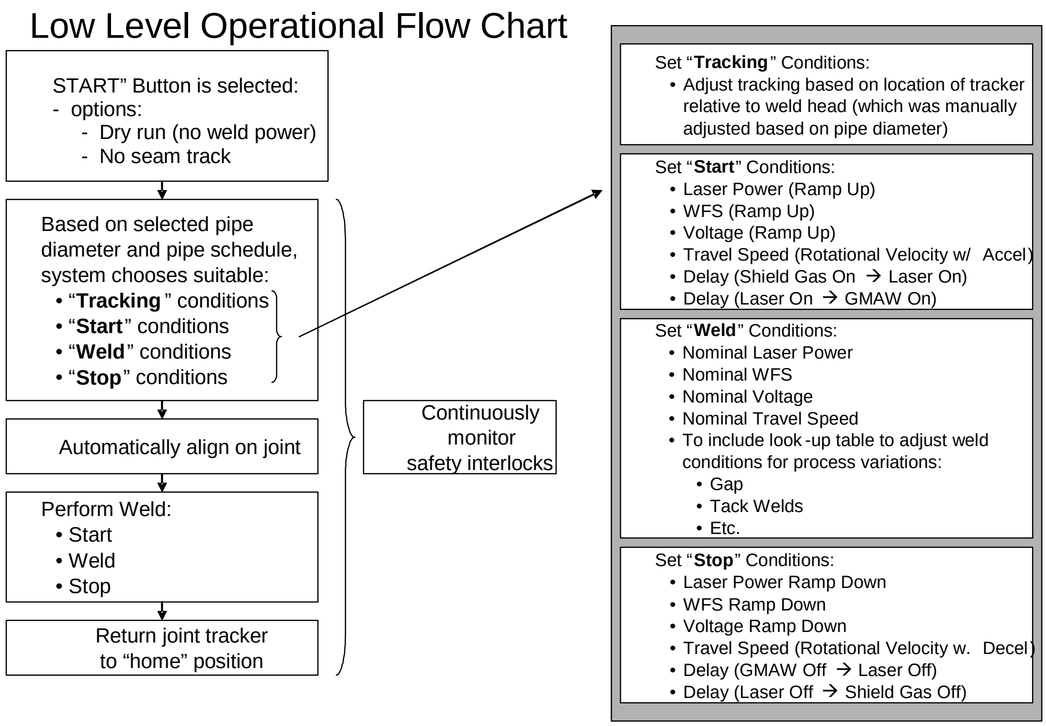

Figure 5. Low Level Workcell Operational Flow Chart.

Note that many GMAW power supplies offer on-board programming of start and stop conditions to prevent stub-in, burnback, crater fill, etc.—it is acceptable to rely on these rather than providing in the weld schedule database and controlling by the Workcell Control System, provided they produce acceptable welds in conjunction with the laser.

1.4. Work Cell Controls and Accessories

A list of controls and indicators available to the operator from within the workcell are listed below in Figure 6.

Manual Controls (pendant)

- GMAW
  - Wire Jog
  - Shield Gas Purge
- Laser
  - Aiming Laser On/Off
- Joint Tracking System
  - Jog +/- Y-axis
  - Jog +/- Z-Axis
- Weld Head Manipulation System (if powered)
  - Jog Up/Down
  - Jog +/- Along Length of Pipe (<15 sec)
  - Go to "Park" Position (<10 sec)
- Rotary Positioner
  - Jog CW/CCW
  - Jog Speed Adjustment
- General
  - E-Stop (halt entire process)

Indicators (pendant)

- Safety Interlock Tripped / Ready to Go
- Shield Gas On
- Laser Power On
- GMAW Power On

Figure 6. List of Controls and Indicators to be provided to the operator on the Workcell Pendant.

A joystick is recommended for jogging of the Joint Tracking System.

A list of additional "nice-to-have" accessories that should be added to the workcell are included for operator efficiency and comfort (see Figure 7).

Workcell Accessories

- 110 VAC receptacles (6)
- Adjustable task lighting
- Gas manifold

Figure 7. List of "nice-to-have" workcell accessories.

2. Hybrid Laser Arc Welding (HLAW) Head

To the maximum extent possible, the HLAW Head should consist of commercial-off-the-shelf (COTS) components. The head shall provide for integration of a laser beam welding (LBW) head and GMAW push-type or push-pull-type gun capable of feeding 0.035 inch or 0.045 inch diameter steel wire (ER70S6 or similar). The head shall be water cooled. The head shall be mounted to an integrated Joint Tracking System to be described later. Cable management issues will be specifically addressed. The head shall have break-away capability or a crash protection cage (roll cage) to prevent damage to the head by unintentional movement or contact.

The HLAW Head shall be provided to Penn State within four months ARO for a duration of three weeks for initial checkout and process development. Additional use of the head by ARL Penn State before delivery of the workcell shall be possible for mutually acceptable periods of time for additional process development and qualification.

The body of the HLAW Head must not interfere with the dimensional envelop of buttweld flange faces for pipes. See Figure 8 for flange face envelope.

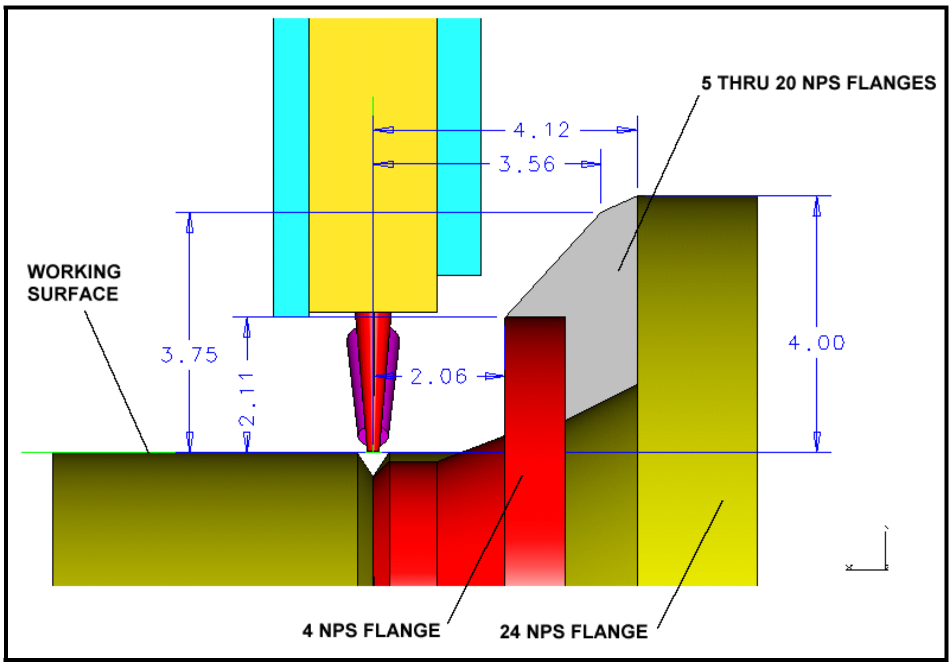

Figure 8. Envelope for flange faces (unit in inches)

2.1. Laser beam welding (LBW) head

The LBW head shall be compatible with a 7 KW fiber laser from IPG Photonics Corporation, Model YLR-7000. The 7 KW fiber laser system will provide a 20 meter armored cable of nominally 600 micron diameter, a red aiming diode laser, and a communications interface that enables laser power and shutter control in real-time. The

welding head shall permit use of the laser's red aiming diode for rough positioning of the weld head prior to welding.

The head shall provide a suitable means to protect the internal optics from weld spatter such as an easily-replaced low-cost protective window, air knife, etc. The laser beam welding head shall be water cooled, allowing continuous processing at a 7 KW power level.

2.1.1. LBW head parameters

Focal length	Nominally ~200 mm *(Negotiable)*
Lens diameter	50 mm nominal
Free aperture	45 mm nominal
Cooling technique	Water cooled as required for continuous operation at 7kW laser beam power
Laser angle with respect to workpiece	Nominally normal to working surface. Laser beam shall be adjustable +/- 5 degrees minimum in the plane parallel to the centerline of a fixtured pipe and +0/-45 minimum in a plane perpendicular to the pipe centerline (see Figure 9)

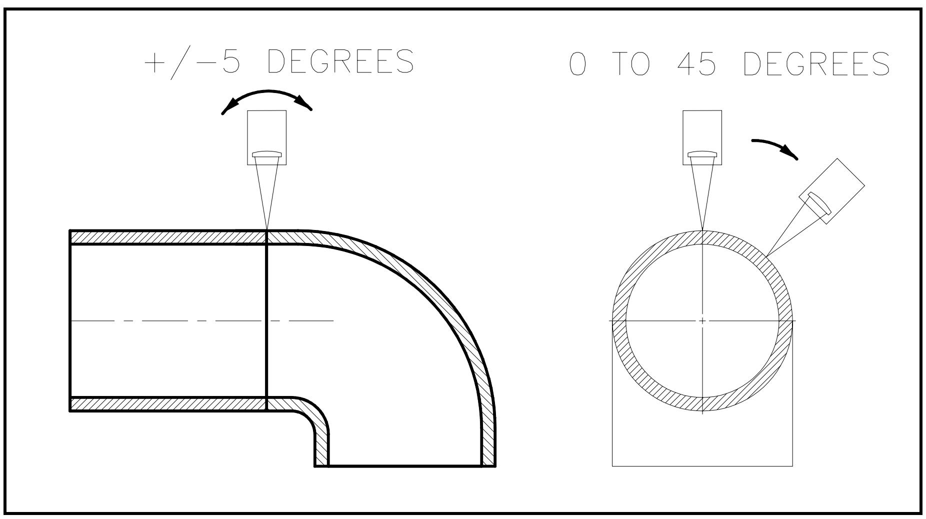

Figure 9. Minimum adjustment range for LBW Head

2.2. Gas metal arc welding (GMAW) gun (torch)

A water-cooled push-type or push-pull type GMAW gun shall be integrally mounted to the LBW head. The tip of the wire electrode (when extended far enough to contact the work surface) shall be positioned to the rear of the focal point of the laser beam (with respect to the direction of travel of the work surface). Contact-tip-to-workpiece distance shall be nominally 19 mm (¾ inch), but adjustable from 12 mm to 25 mm (½ inch

to 1 inch) minimum. The nominal distance between the wire-workpiece contact and the laser beam focal point shall be 2 mm, but shall be adjustable from 0 mm to 20 mm minimum *(Negotiable)*. The angle of the wire electrode relative to the axis of the laser beam shall be nominally 25^o. This angle shall be adjustable from 20^o to 45^o minimum with respect to the laser beam. See 10.

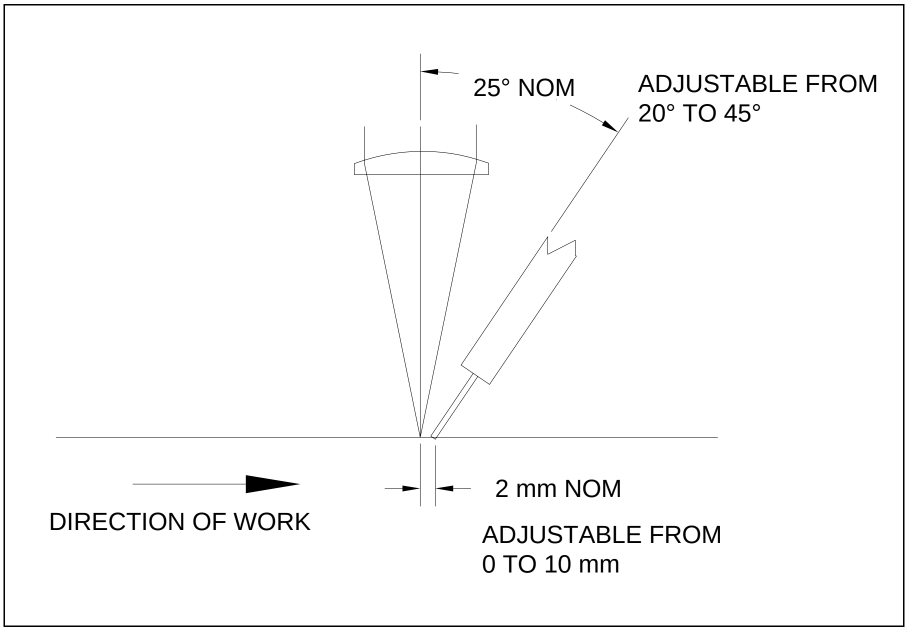

Figure 10. GMAW gun to LBW head relationship ***(Note: adjustment range should read "0 mm to 20 mm", not "0 mm to 10 mm" as specified in the illustration).***

3. Integrated Joint Tracking System

An integrated Joint Tracking System shall be provided. This system shall perform automatic non-contact joint tracking during pipe welding. The pipe may have mill scale or rust on the surface, but the joint will be machined. The HLAW Head shall be mounted to this system.

This system shall be capable of tracking the joint and locating the focused beam spot to within ±0.0025 inch of the joint centerline and within ±0.0025 inch of the desired distance from the working surface at a weld speed up to 80 inches per minute. The system shall provide a tracking sensor and linear stages with a minimum motion range of ±3 inches in the y-direction (transverse to the weld path), and ±3 inches in the z-direction (vertical), and be capable of supporting the sensor and HLAW Head.

The system shall also include software that provides information about the joint such as vertical mismatch, gap, angle, presence and size of tack-welds, and provides for user-defined look-up tables and/or formulas (i.e. weld schedule database) to adjust the weld schedule in real-time as necessary to maintain weld quality. The system shall provide a communications interface that enables real-time adjustment of laser power, wire feed speed, weld voltage, and/or travel speed (i.e. must be able to communicate in real-time with the Laser With Chiller, the GMAW Power Supply And Wire Feeder, and the Rotary Positioner).

This system shall provide:

- two motorized linear slides for moving the head in the transverse and vertical directions (Y and Z), see Figure 111111
- a forward looking sensor (camera), and
- control system.

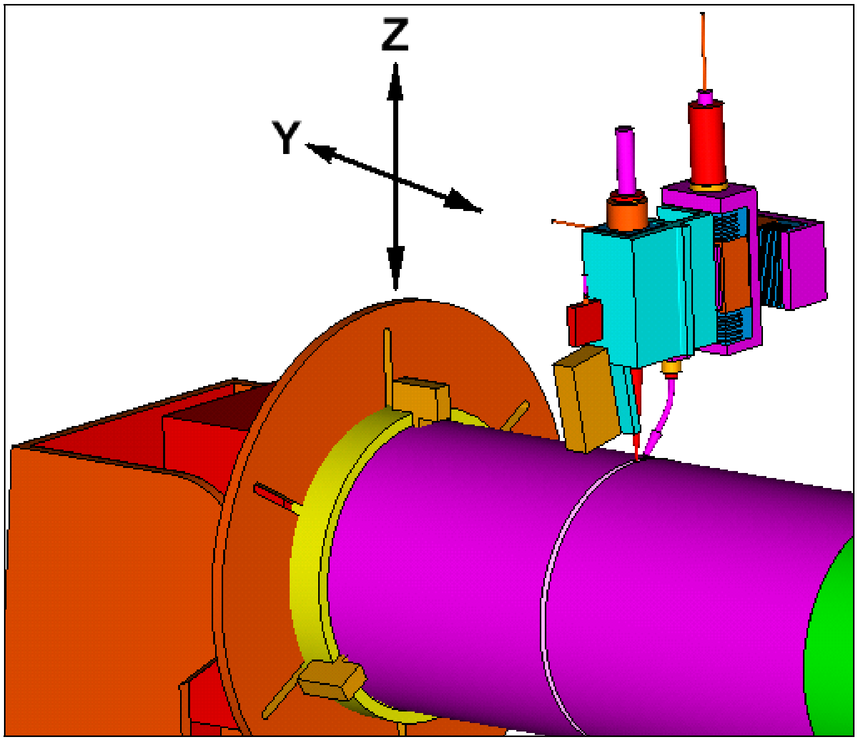

Figure 11. Directions of travel for joint tracking system.

3.1. Motorized cross-slides

The motorized cross slides shall be capable of supporting the HLAW Head. The slides shall conform to the following specifications:

Positioning accuracy, lateral	±0.0025 inch (±62.5 µm)
Positioning accuracy, vertical	±0.0025 inch (±62.5 µm)
Y (lateral) travel stroke	±3 inches (~ ±75 mm) minimum
Z (vertical) travel stroke	±3 inches (~ ±75 mm) minimum
Maximum tracking speed	80 ipm (~ 2 m/min)
Maximum stage velocity	as required to track at 80 ipm (TBD)

3.2. Joint tracking sensor

A joint tracking sensor shall be provided to allow the HLAW Head to track the weld joint in real-time during welding. This sensor shall be attached to the HLAW head.

The position of the sensor shall be manually adjustable to a minimum of 3 hard set points, that enable adequate tracking for various ranges of pipe diameter (dimensional details are TBD). See Figure 12.

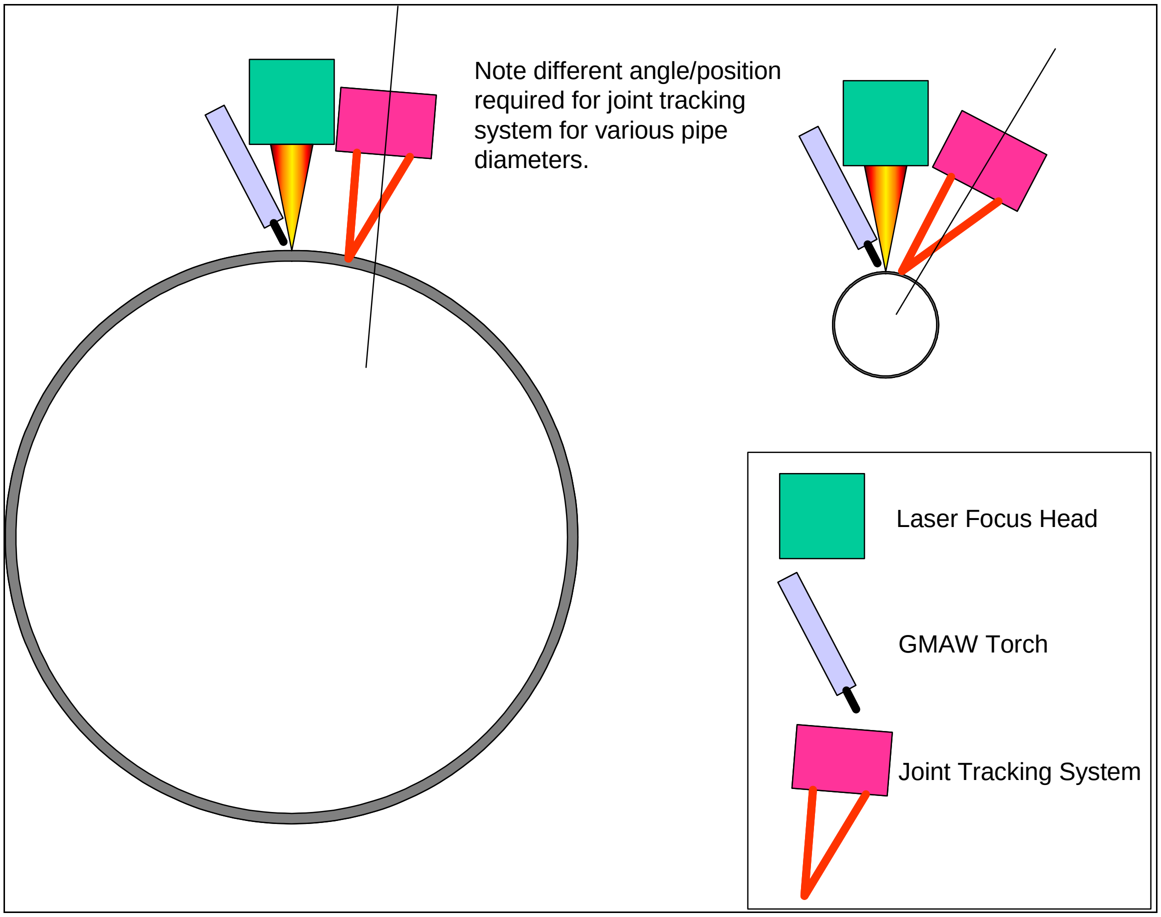

Figure 12. Illustration of need for multiple positions of sensor relative to HLAW head for different size pipes.

The sensor shall also offer optional software that enables joint geometry measurement and automatic "visual" post-weld inspection of the weld joint.

The sensor shall provide provisions to prevent weld spatter from contacting its lens, such as an air knife, replaceable window, etc. The sensor shall be capable of continuous operation during welding with the HLAW Head and incorporate water cooling as required.

Specifications for the sensor are as follows:

Minimum field of view, lateral	±0.25 inch (12.7 mm)
Minimum field of view, depth	±0.25 inch (6.4 mm)
Vertical resolution	0.001 inch (25 micron)
Lateral resolution	0.001 inch (25 micron)

3.3. Joint Tracking Control system

The joint tracking control system shall provide the necessary software and hardware for controlling and driving the cross slides, operating the joint-tracking sensor, and providing feedback to the workcell control system. The control system shall have an operating bandwidth of at least 60 Hertz.

The system shall also provide software that supplies information about the joint such as vertical mismatch, gap, angle, presence and size of tack-welds, and provides user-defined look-up tables and/or formulas to adjust the weld schedule in real-time as necessary to maintain weld quality. The system shall provide a communications interface that enables real-time adjustment of laser power, wire feed speed, weld voltage, and/or travel speed (i.e. must be able to communicate in real-time with the Laser With Chiller, the GMAW Power Supply And Wire Feeder, and the Rotary Positioner).

The joint tracking control system shall provide an interface to the Workcell Pendant as required to allow the operator to jog the Y and Z axes.

Figure 13. Image of Integrated Joint Tracking System with Laser Welding Head is a potential candidate (image from ServoRobot)[4].

[4] ARL Penn State has conducted extensive preliminary negotiations with ServoRobot, and should be consulted during selection of the Joint Tracking System.

4. Weld Head Manipulation System

A Weld Head Manipulation System shall be provided that allows the focus point of the laser beam to be positioned anywhere in the minimum welding volume with an accuracy equal to or better than the Joint Tracking System sensor's field-of-view (FOV), nominally ±0.25 inches. This volume is defined as a 96 inch x 16 inch rectangle (with its lower edge offset 1 inch from the Rotary Positioner centerline for welding of 4 inch NPS pipe with potential misalignment) rotated about the centerline through an angle of 45 degrees minimum from top dead center. The focus point shall be capable of being located within 4 inches from the Rotary Positioner chuck in the axial (Y) direction. See Figure 14114 for the welding volume description.

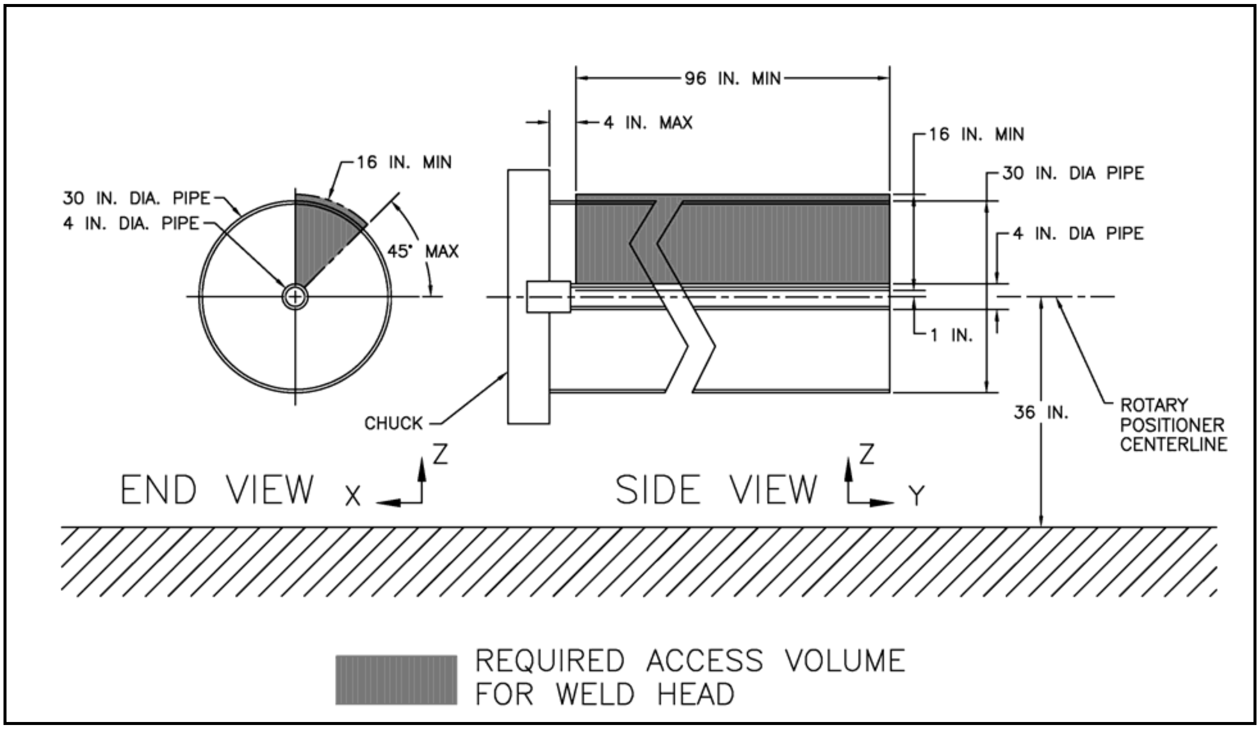

Figure 14. Welding volume for workcell

COTS components shall be used to the maximum extent possible for the manipulation system. The manipulation system may be powered or manually operated, and controls shall be easily accessible for the operator. If a manual drive is used for the vertical axis, the moving mass must be suitably balanced using a spring, pneumatic cylinder, counter-balance or other means. The axes shall have mechanical limits to prevent over-travel. Powered axes shall have adjustable speed control and electrical limits as well.

After the HLAW Head is positioned, brakes or other suitable means shall be employed on the manipulation system to prevent movement during welding.

The manipulation system must provide sufficient rigidity to counteract forces generated by head accelerations during joint tracking such that the head can maintain adequate track of the weld joint.

The sliding and/or rolling surfaces of the manipulation system shall be adequately protected for the intended welding environment. Potential protection components may include way covers with positive pressure.

The manipulation system must allow the head to translate or rotate out of the working area such that components can be safely loaded/unloaded from the workcell without damaging the weld head. This is referred to as the park position. The park position must allow slinging and lifting of a 30 inch diameter pipe from the workcell. Overhead cranes are used to move the welded components.

Suitable park positions include a transverse movement that provides at least 16 inches of clearance from the weld head to the positioner centerline (A in Figure 9) and/or a longitudinal movement rearward of the mounting chuck (B in Figure 9).

Traversing the HLAW Head from the extreme corners of the minimum welding area shown in Figure 9 shall take no longer than 15 seconds. Traversing the head to and from the park position shall take no longer than 10 seconds.

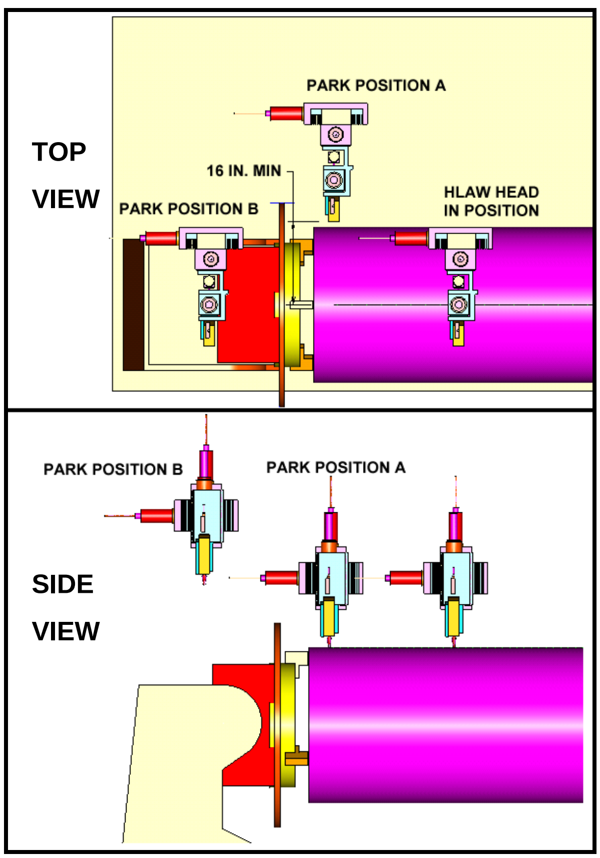

Figure 9. Potential head park locations

The manipulation system may be either mounted to the base structure or ancillary structures mounted to the base, such as vertical supporting walls, etc. Examples are shown in Figure 10.

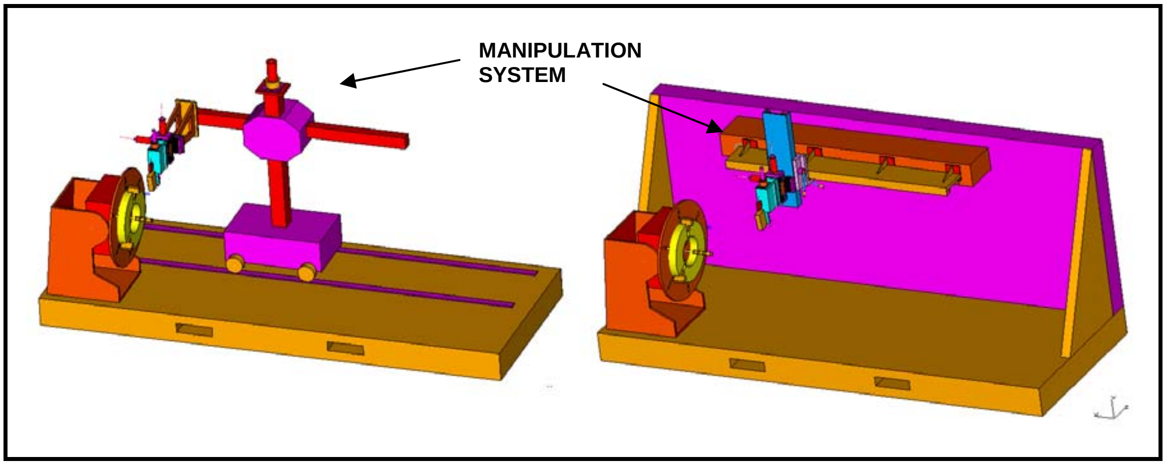

Figure 10. Examples of Weld Head Manipulation Systems.

Figure 11. Image of Weld Head Manipulation system shown as a possible example only (from Preston Eastin).

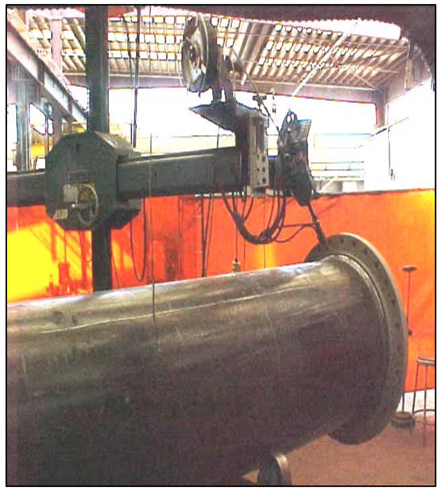

Figure 12. Image of Weld Head Manipulation System shown as a possible example only (from NASSCO).

5. Rotary Positioner

A rotary positioner shall be mounted to the base plate of the workcell for rotating components during welding. The positioner shall be computer controlled during the welding operation and velocity shall be adjustable in real-time via a communications interface that is compatible with the joint tracking system (analog/RS232/other). A jog capability for both CW and CCW rotation shall be controllable via both the Workcell Pendant and the Workcell control system. ARL will provide a standard COTS inside and outside diameter self centering chuck for pipe ranging from 4 inch NPS to 30 inch NPS.

The table speed shall be fully adjustable in real-time during the welding process to accommodate varying thicknesses of the joint, tack welds, etc. based upon control signals from the joint tracking system. The bandwidth for the table's response to changing speed commands shall be at least 10 Hertz.

The positioner shall conform to the following specifications:

Weight capacity	2,000 pounds
Rotational torque	25,000 inch-pounds minimum
Required welding speed range	0.1 to 8 RPM minimum rotational velocity range (corresponds to linear welding speed of 10 ipm to 100 ipm)
Welding speed accuracy	0.5 % of set speed
Response bandwidth	10 Hertz minimum
Centerline to base distance	36 inches
Table diameter	diameter as required to fixture 30 NPS pipe
Electrical ground	2 each 600 amp spring-loaded mechanical ground
Control	Workcell Pendant, Joint Tracking System, and Workcell Control System (control of speed, direction, total rotation angle, start, stop, accel, decel)

Figure 13. Image of Rotary Positioner shown as a possible example only (from NASSCO).

6. GMAW Power Supply And Wire Feeder

A constant voltage GMAW Power Supply And Wire Feeder system is required to interface with the gun mounted to the HLAW Head for GMAW welding. This unit may be positioned off of the Workcell Base/Support Structure.

The GMAW system shall be provided to ARL Penn State for initial checkout and process development. Additional use of the GMAW system by ARL Penn State before delivery of the workcell shall be possible for mutually acceptable periods of time for additional process development.

6.1 Power Supply

The power supply shall be digitally controlled via a communications link to both the Joint Tracking System and to the Workcell Control System. The power supply shall provide the capability to monitor the process variables, including arc current, voltage, and wire feed speed, in real time. The power supply shall digitally control the wire drive system and voltage (i.e. constant voltage power supply).

Power supply specifications (minimum):

Rated output, 100% duty cycle	450A/38V
Rated output, 60% duty cycle	570A/43V
Output range	5-570 Amps DC

6.2 Wire Feeder

The wire feeder shall be digitally controlled directly by the power supply. It shall have suitable feedback to ensure precise control of wire feed speed. The wire drive system shall provide at least one gas solenoid to control shielding gas for the welding process.

Wire feed system specifications:

Wire diameter range (min)	0.035 – 0.045 inch
Feed speed	50 – 500 ipm
Speed accuracy	1% of set speed

Figure 14. Image shown as a possible example only (from Lincoln Electric).

The system shall provide a communications interface that enables control of wire feed speed, weld voltage, shield gas on/off in real time from the Workcell Control System and from the Joint Tracking System (analog/RS232/other). An ON/OFF switch for the shield gas and switches for wire jog (both forward and reverse) shall be controllable via from both the Workcell Pendant and the Workcell Control System.

7. Laser with Chiller as Required

A 7kW Fiber Laser (with a chiller) as required will be leased by ARL Penn State from a commercial supplier for use in the demonstration system. The system will include a fiber for beam delivery. The fiber core diameter shall be 600 microns.

Figure 15. Image shown as a possible example only (from IPG).

8. Workcell Pendant / Control System

A Workcell pendant / control station will be provided to allow the operator to control and monitor the following:

A list of controls and indicators available to the operator from within the workcell are listed below in Figure 16.

Manual Controls (pendant)

- GMAW
  - Wire Jog
  - Shield Gas Purge
- Laser
  - Aiming Laser On/Off
- Joint Tracking System
  - Jog +/- Y-axis
  - Jog +/- Z-Axis
- Weld Head Manipulation System (if powered)
  - Jog Up/Down
  - Jog +/- Along Length of Pipe (<15 sec)
  - Go to "Park" Position (<10 sec)
- Rotary Positioner
  - Jog CW/CCW
  - Jog Speed Adjustment
- General
  - E-Stop (halt entire process)

Indicators (pendant)

- Safety Interlock Tripped / Ready to Go
- Shield Gas On
- Laser Power On
- GMAW Power On

Figure 16. List of Controls and Indicators to be provided to the operator on the Workcell Pendant (note Wire Jog shall be forward and reverse)

9. Workcell Control System / Programming Station

The Workcell Control System shall provide an interface for operations such as:

- provide operator interface for selection of weld pipe diameter and schedule,
- initiating the process and providing necessary system controls that the joint tracking system does not provide,
- provide authorized users capability to adjust weld schedule database, and
- provide authorized users ability to specify welds that are not full 360 degrees.

Software should be open architecture to enable authorized users the ability to make modifications as required. Source code shall be provided. It shall consist of a computer or computer coupled to a PLC. The system shall be capable of continuous operation in a typical welding environment. The system shall continuously monitor interlocks as required. Potential functional block diagrams (depending on control architecture) are shown in Figure 17 and 24.

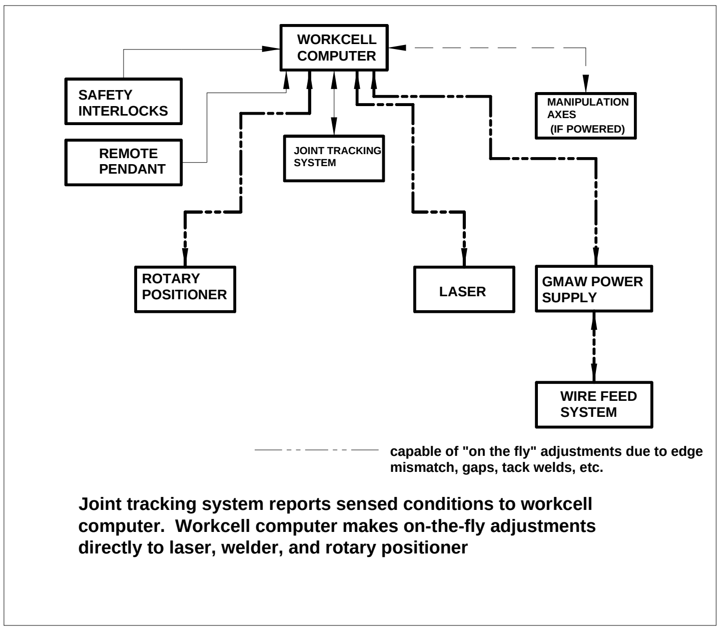

Figure 17. Functional block diagram for workcell control system: workcell computer makes on-the-fly adjustments

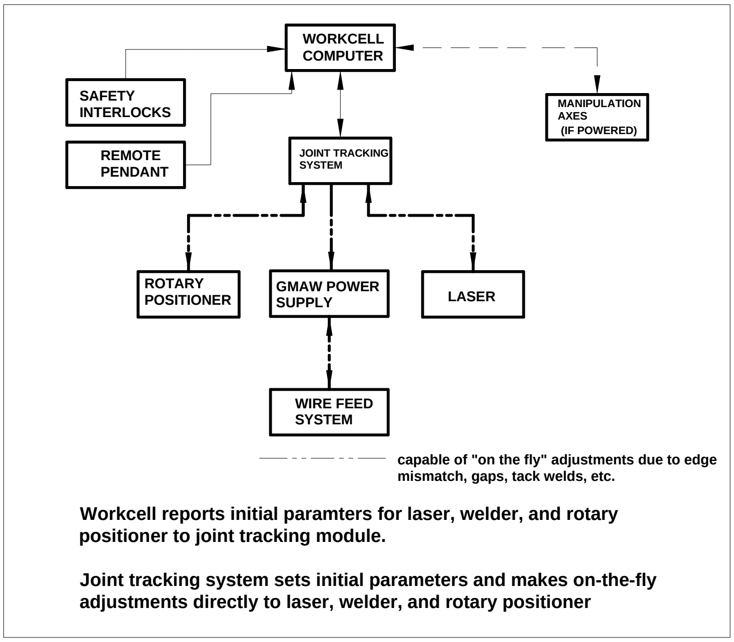

Figure 24. Functional block diagram for workcell control system: joint tracking computer makes on-the-fly adjustments

An anticipated welding sequence in the workcell is as follows:

1. Operator loads tack-welded components into workstation and installs components onto rotary positioner using additional support rollers and stands as required
2. Operator moves weld head from **PARK** position to welding position with accuracy equal to or better than tracking sensor's FOV. (if powered, using remote control)
3. Operator locks Y and Z axes of manipulation system to prevent head movement (if applicable)
4. Operator selects the pipe diameter and schedule –OR– sets the parameters for the weld based on pipe diameter, wall thickness, material, and joint characteristics. Parameters include: laser power, rotation speed, shielding gas flow rate and composition, laser focal point to arc spacing distance[5] and/or angle, filler wire type, diameter and feed rate, arc voltage and current, and torch work distance.
5. Operator starts sequence to position head into welding position using joint tracking module (press **TRACK JOINT** button).
6. Joint tracking sensor scans joint and positions Y and Z axes appropriately for desired standoff distance and joint centerline.

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[5] *laser focal point to arc spacing distance* is defined as the gap between the focal point of the laser beam and the tip of the wire electrode when it is extended far enough to contact the surface of the work

7. Operator verifies head location using visible aiming diode laser. If positioning is incorrect, operator repeats previous step
8. [OPTIONAL] Operator initiates joint tracking test on components to be welded using **DRY RUN** button to ensure that joint is track-able for the full rotation.
9. Operator leaves workcell, closes safety doors, and starts welding sequence (press **START** button)
    - Rotary table accelerates to desired welding speed
    - "Begin weld" sequence:
        a. Laser shutter opens at specified rotation angle (or time interval)
        b. GMAW power supply applies arc power and wire feeder supplies wire at specified rotation angle (or time interval)
    - "End weld" sequence:
        a. Laser shutter closes at specified rotation angle (or time interval)
        b. GMAW power supply removes arc power and wire feeder stops at specified rotation angle (or time interval)
        c. Rotary table decelerates to zero at specified rotation angle (or time interval)
    - Workcell computer stores all parameters that are adjusted in real time during welding, such as:
        a. rotational velocity
        b. GMAW voltage and current
        c. wire feed speed
        d. laser power, etc.
10. Operator positions head back to park position
11. Operator removes components from workcell

10. Base/Support Structure

A base structure(s) shall be provided that accommodates the Rotary Positioner, Weld Head Manipulation System, Joint Tracking System, and HLAW Head. It shall be movable by a fork truck. It shall have sufficient rigidity to safely support the attached components during transport. A means shall be provided to level the base.

The base/support structure may be of new design and fabrication or modification of existing or prefabricated structures or components. For example, with modifications, a cargo transport container or conex box may suffice.

Note that if the Base/Support Structure also serves as the Safety Enclosure, then it must provide a laser-safe ceiling or overhead cover that is easily removable or retractable to permit easy access of pipe assemblies via overhead crane.

Figure 18. Image shown as a possible example only (from Allied Container).

11. Safety enclosure

The function of the safety enclosure is to prevent laser energy from escaping the workcell area. The enclosure shall contain the base structure and the associated Rotary Positioner, Weld Head Manipulation System, HLAW Head, and Joint Tracking System.

A safety light shall be mounted on outside of workcell with mounting and light sequencing in accordance with ANSI Z-36.

The enclosure shall allow the operator to readily load and un-load components from the workcell using an overhead crane. See Figure 26. Alternately, if a ceiling for the enclosure is required, a job crane may be incorporated at NASSCO. The enclosure shall also allow the operator to have general access around the components to be welded for tasks such as initial location of the weld head, monitoring of the head tracking system, and post weld visual inspections. The enclosure shall have a minimum of one access door.

Figure 26. Overhead crane used to move components for welding

The enclosure shall be transportable via truck to San Diego, CA. The enclosure and base may or may not be integral. It may be of new design and fabrication, or modification of existing or prefabricated structures or components. For example, with modifications, a cargo transport container or conex box may suffice.

The enclosure shall provide forced ventilation of the workcell with suitable exhaust collection and filtration. It shall also allow real-time monitoring of the welding process via a viewing window and wall-mounted video screens. See Figures 27 and 28 for enclosure examples.

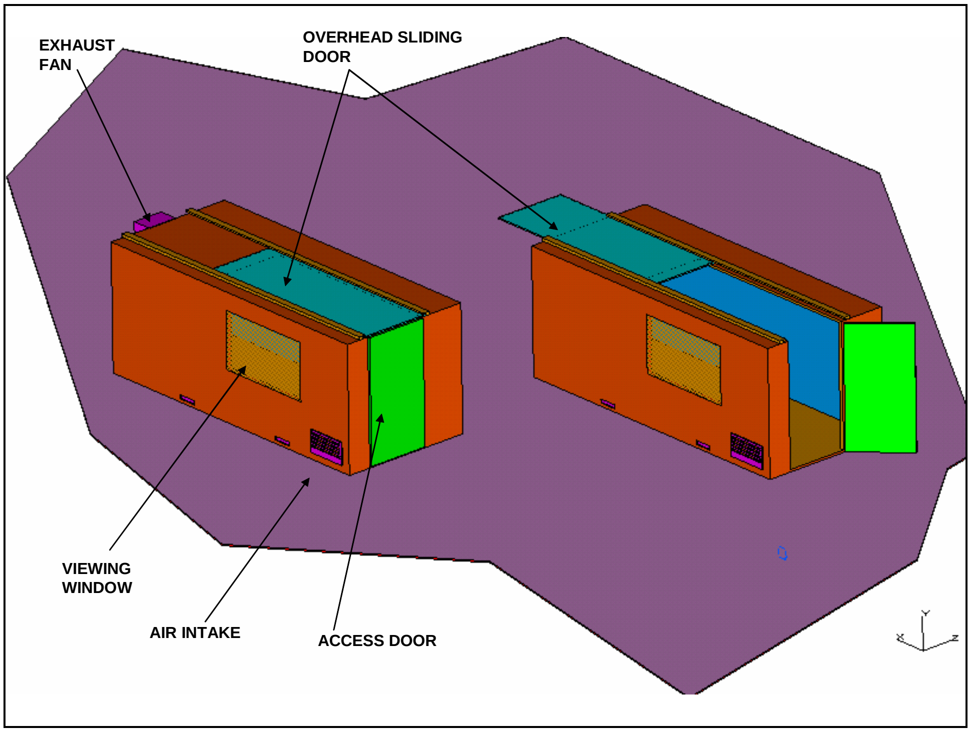


Figure 27. Example of safety enclosure—hinged access door

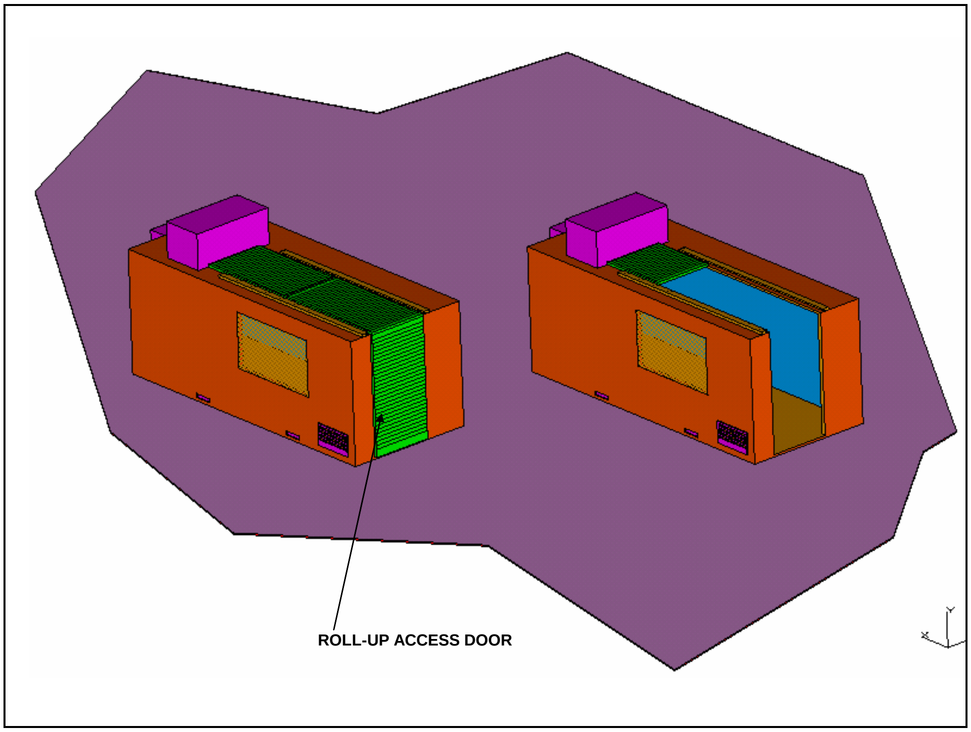


Figure 28. Example of safety enclosure—roll-up access door

11.1 Viewing Window/Video monitors

A window shall be incorporated into the wall of the enclosure to allow viewing of the welding process by the operator. The window shall provide laser beam and GMAW arc safety. The window shall be of suitable size to allow a minimum of three people to comfortably view the process.

The enclosure shall also provide two video cameras with exterior mounted video screen(s) for monitoring the process. One camera shall provide a close-up view of the process while the second provides an overall system-level view.

APPENDIX B. Training Manual – Overview of System Components and Software

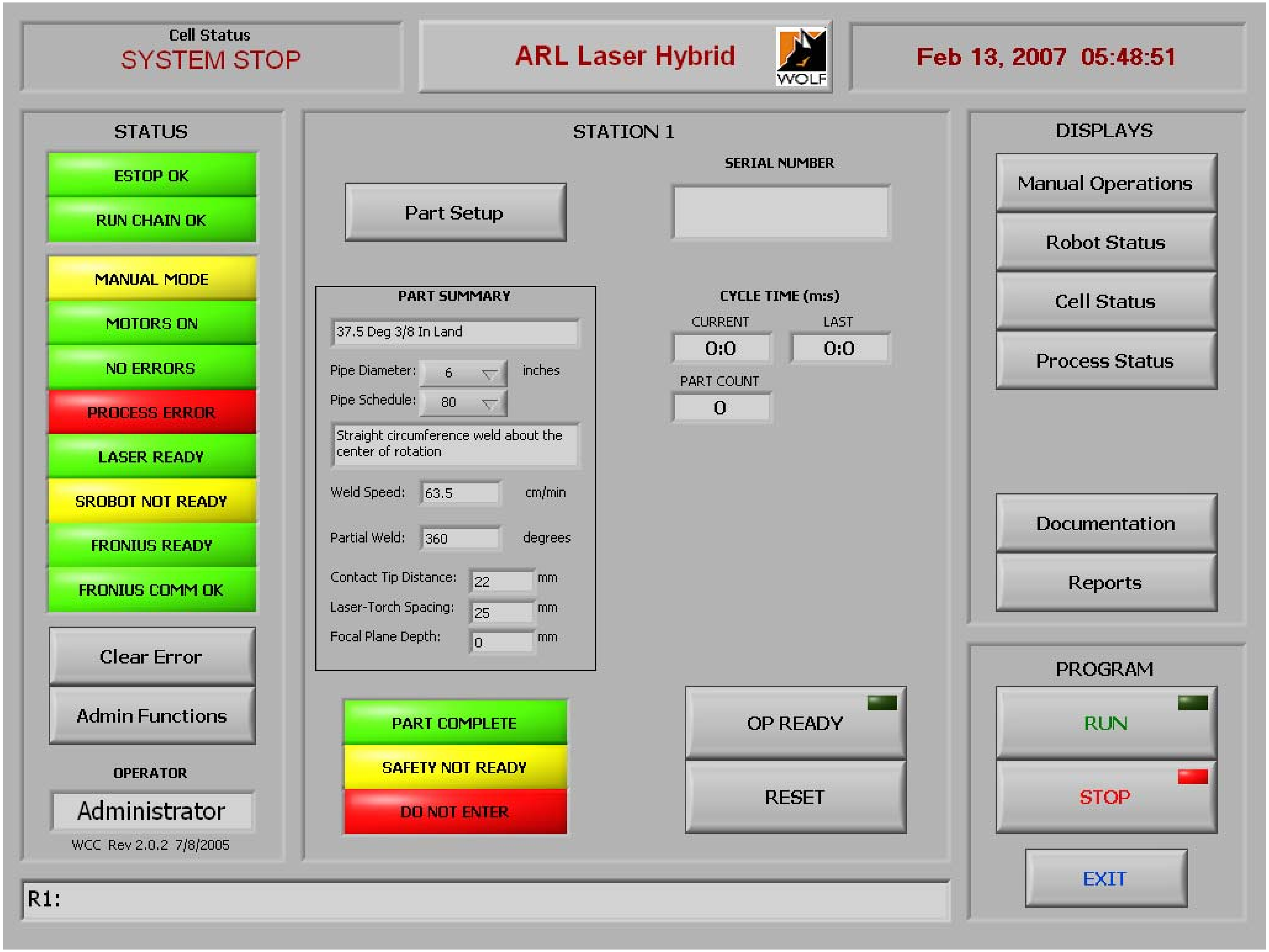
System Components

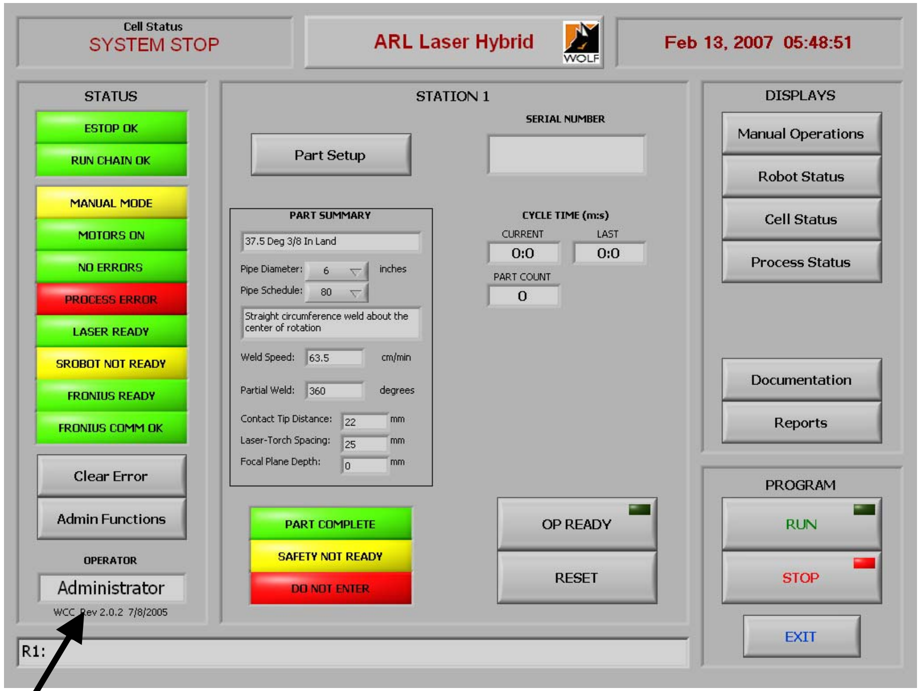
- Wolf Cell Controller
    - Operator Interface
    - **How to define and execute a weld**
- ServoRobot Seam Tracking System
- IPG Laser System

Intentionally Blank

Wolf Cell Controller (WCC)

Wolf Cell Controller (WCC)
Main Screen – 1 of 1



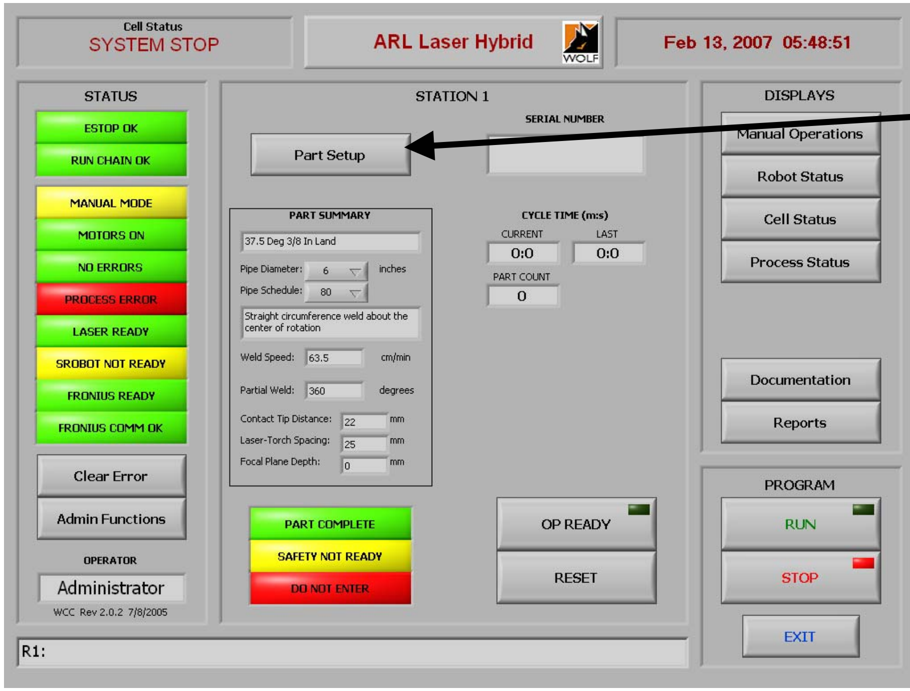


<u>Passwords</u>

Administrator: a

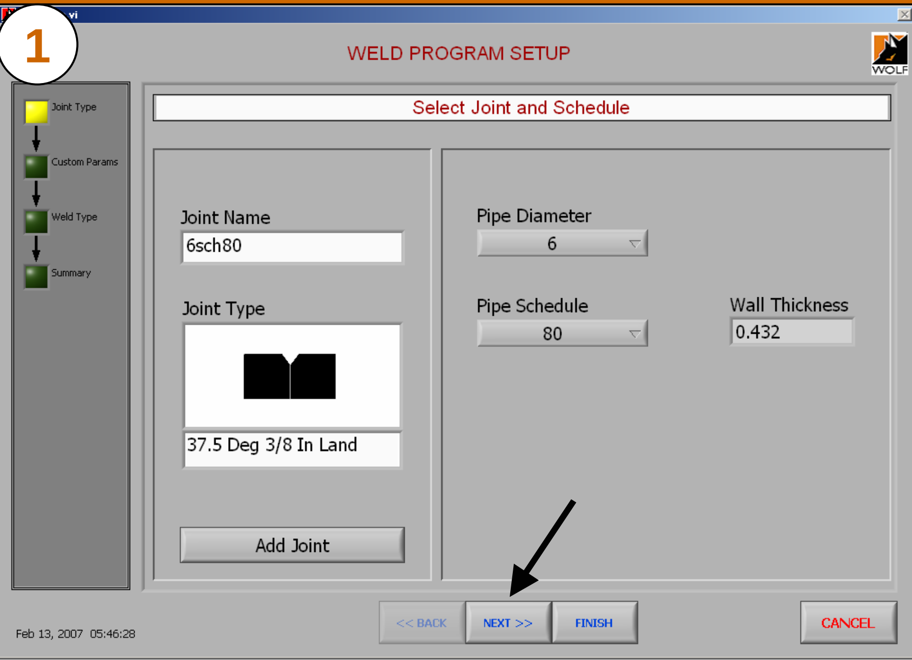
Operator: o

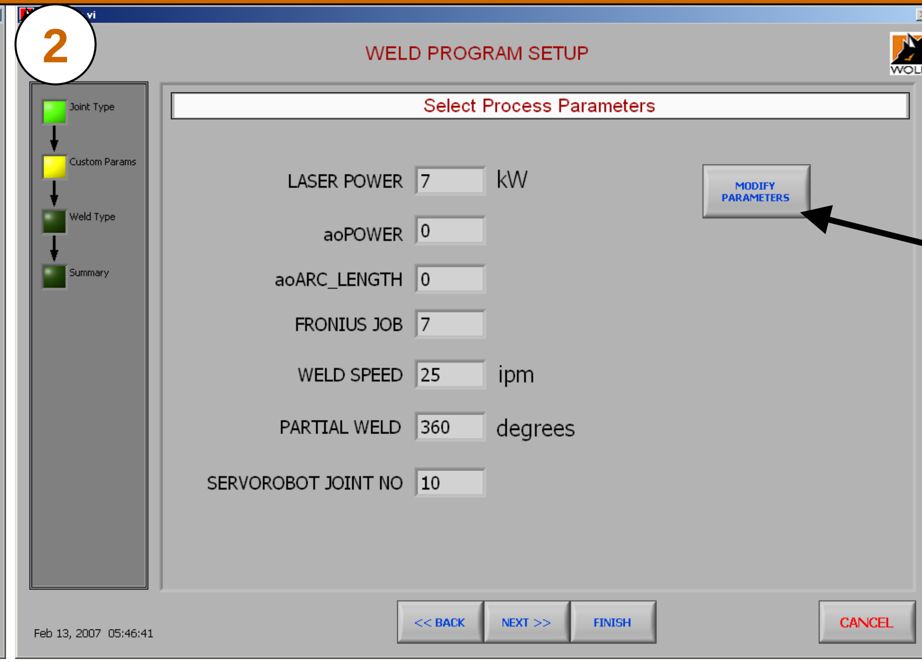
Wolf Cell Controller (WCC)
Part Setup – 1 of 5

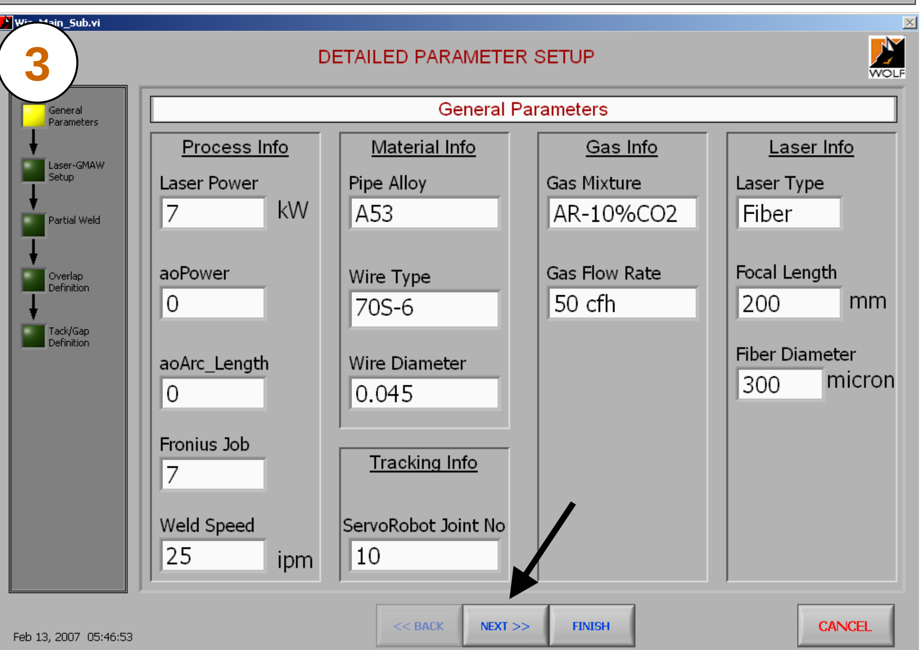


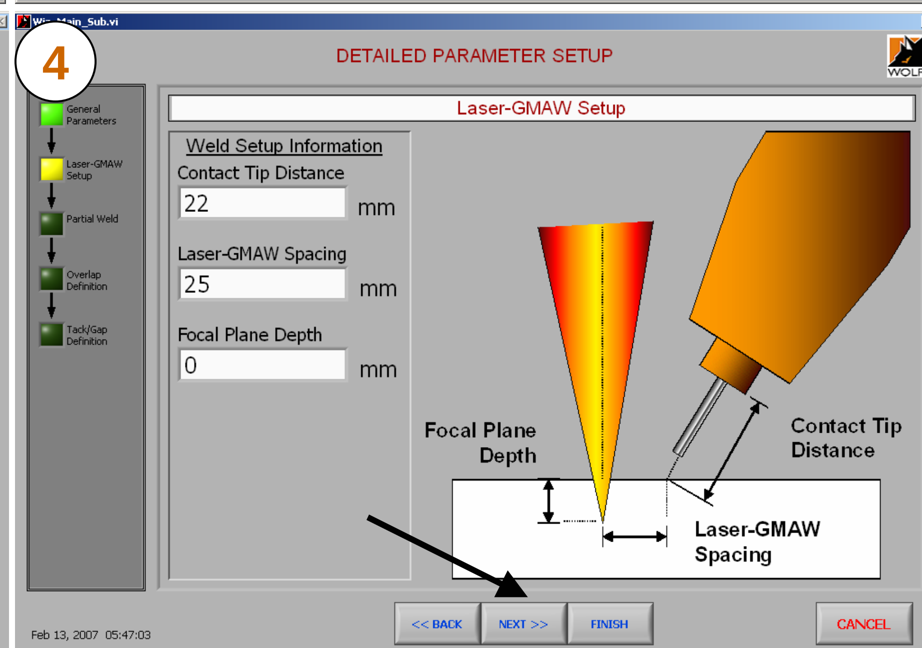
To select part
- or -
To define process parameters (admin).

Wolf Cell Controller (WCC)
Part Setup – Essential Variables – 2 of 5

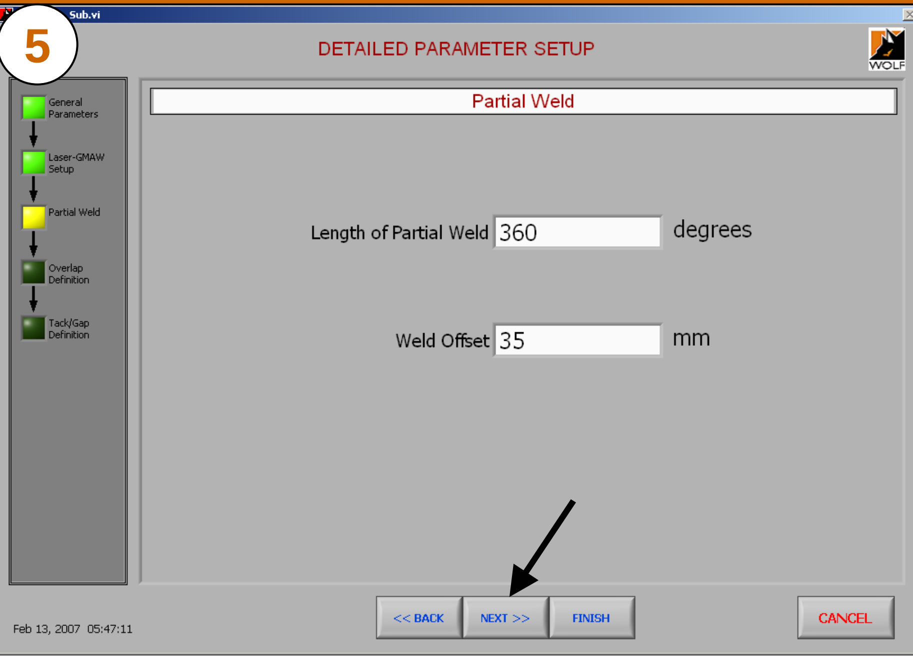


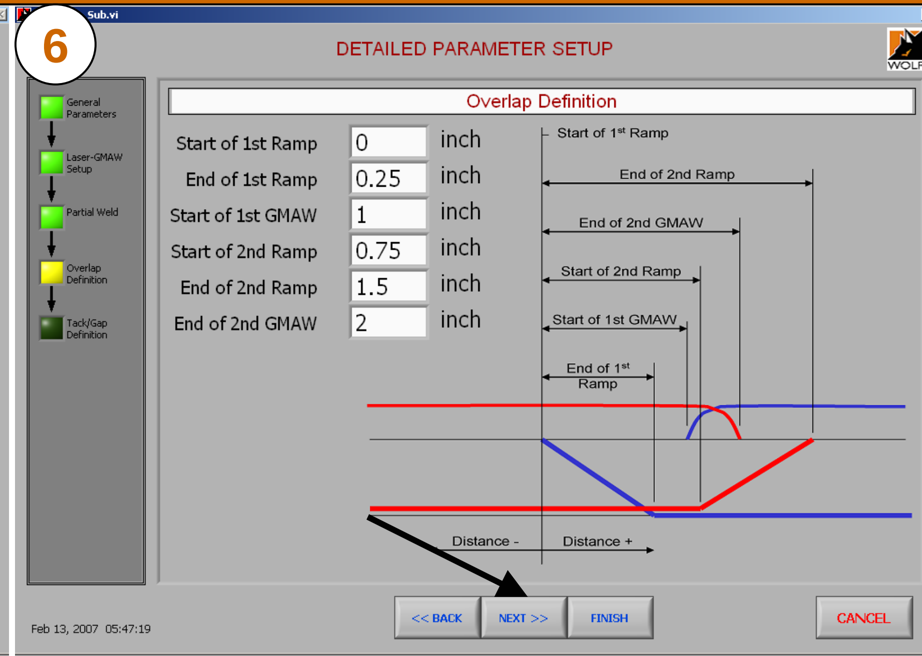


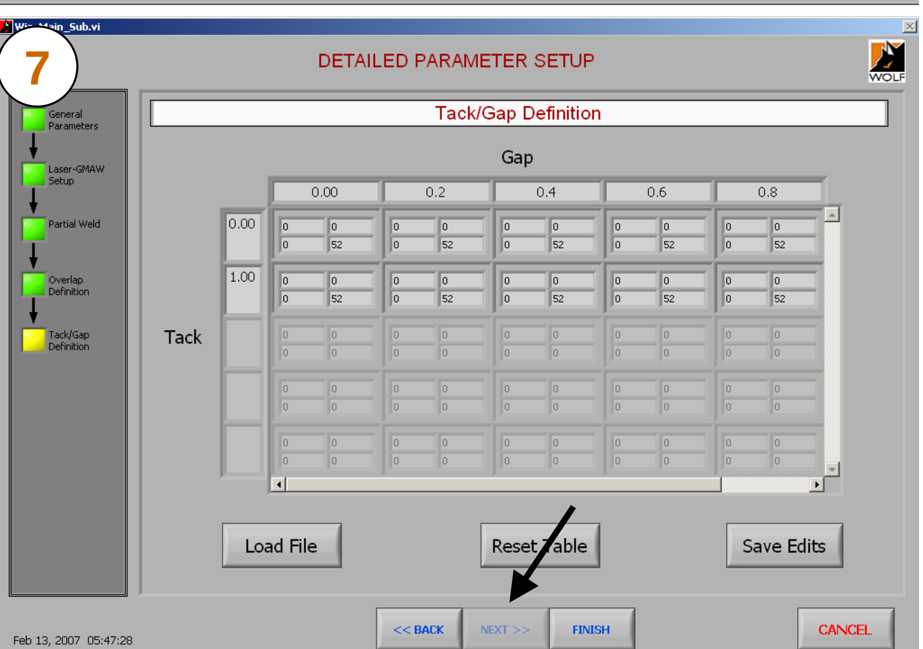


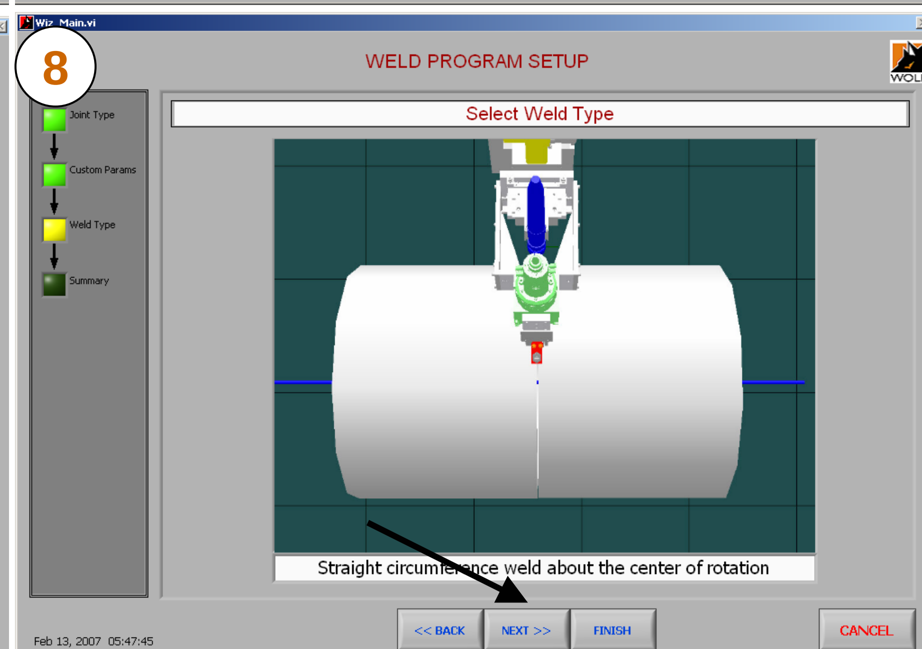


Wolf Cell Controller (WCC)
Part Setup – Essential Variables – 3 of 5

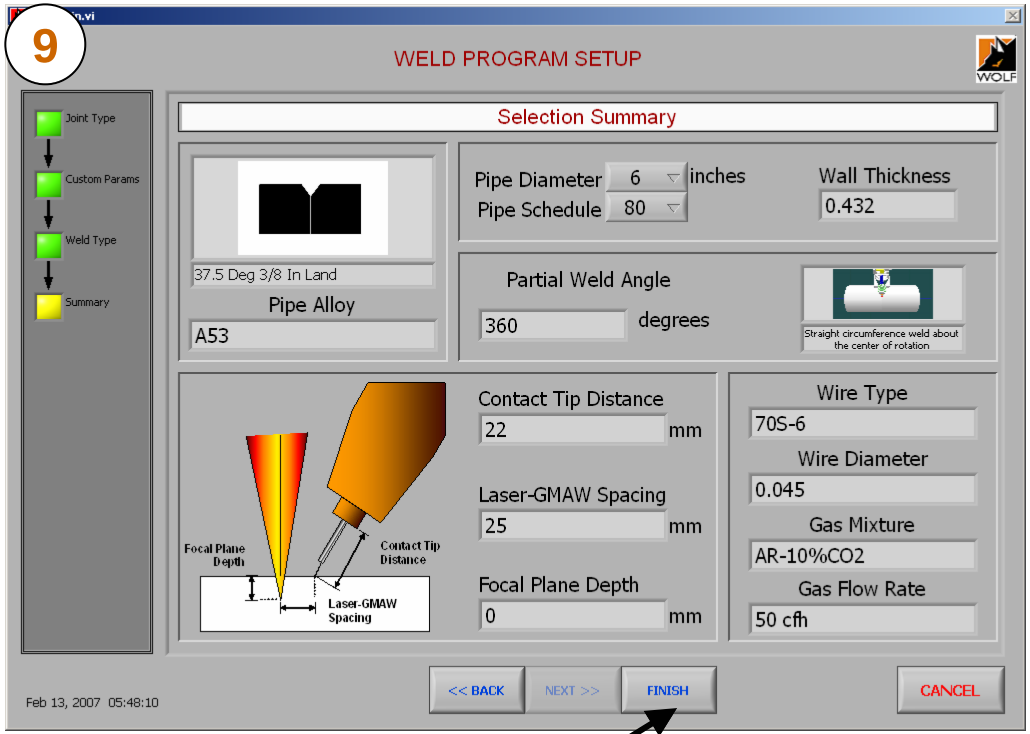


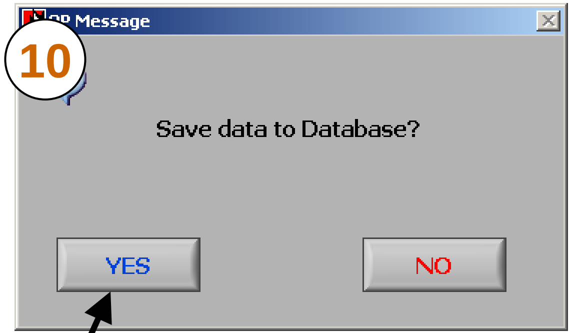




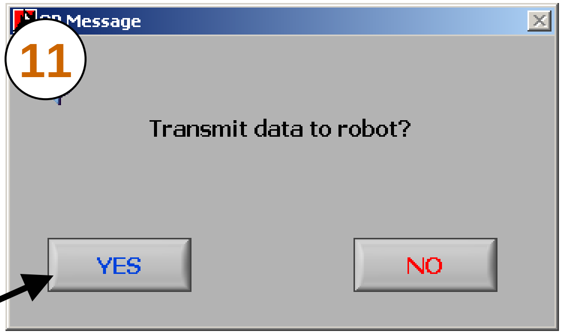


Wolf Cell Controller (WCC)
Part Setup – Review & Download – 4 of 5



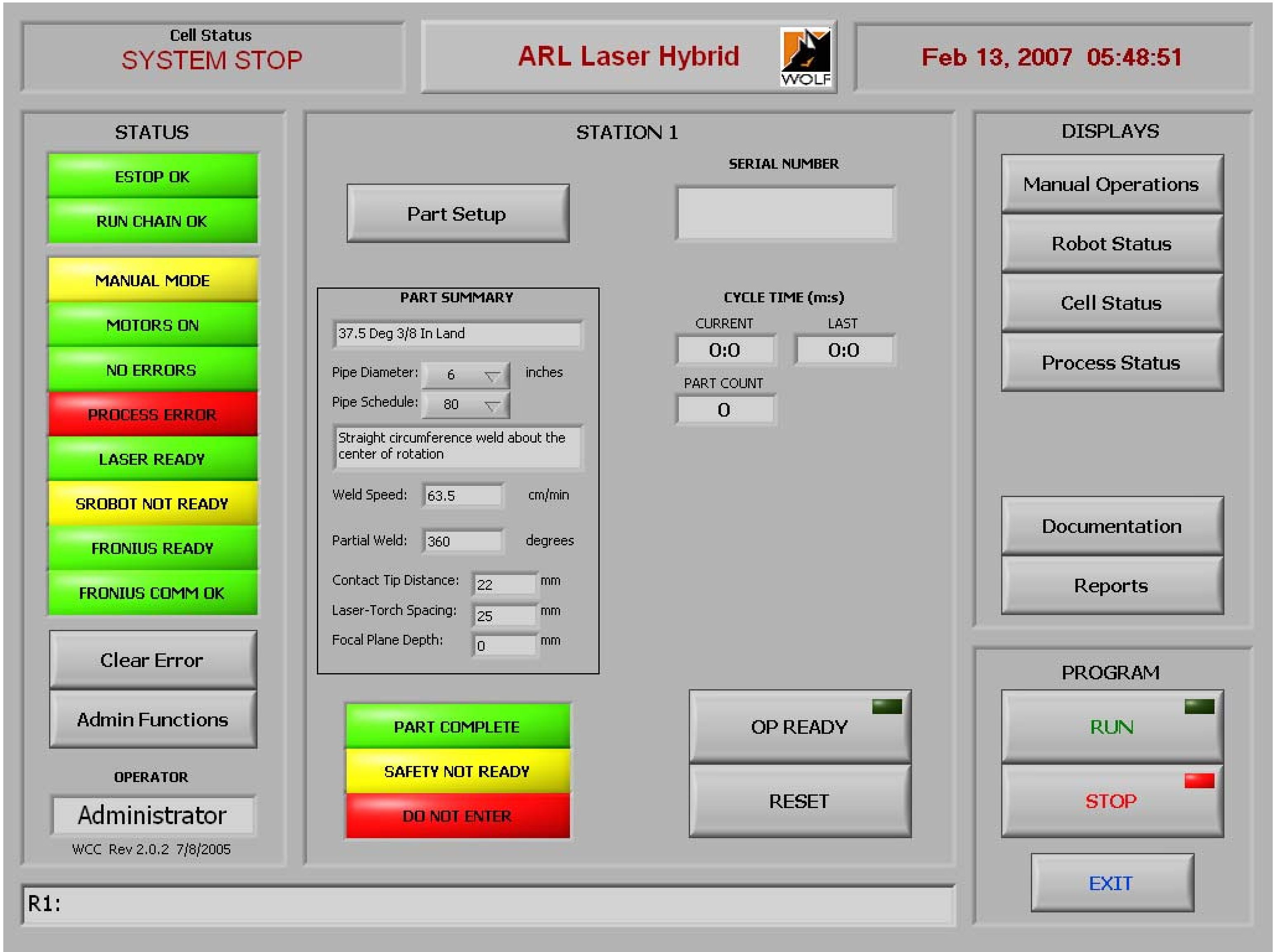


To store the modified parameters…



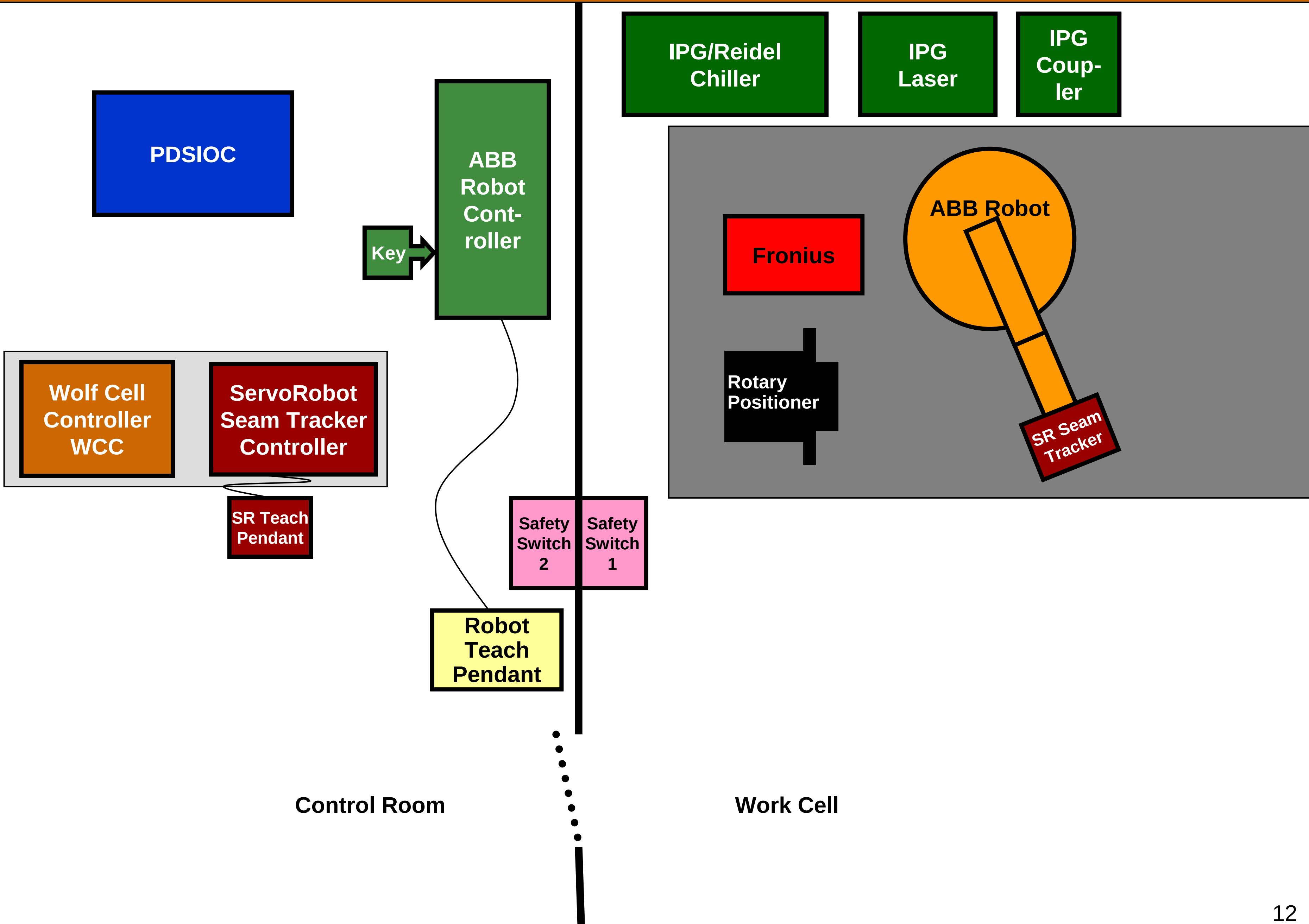
To transfer the parameters to the robot…

Wolf Cell Controller (WCC)
Part Setup – Summary on Main Screen – 5 of 5



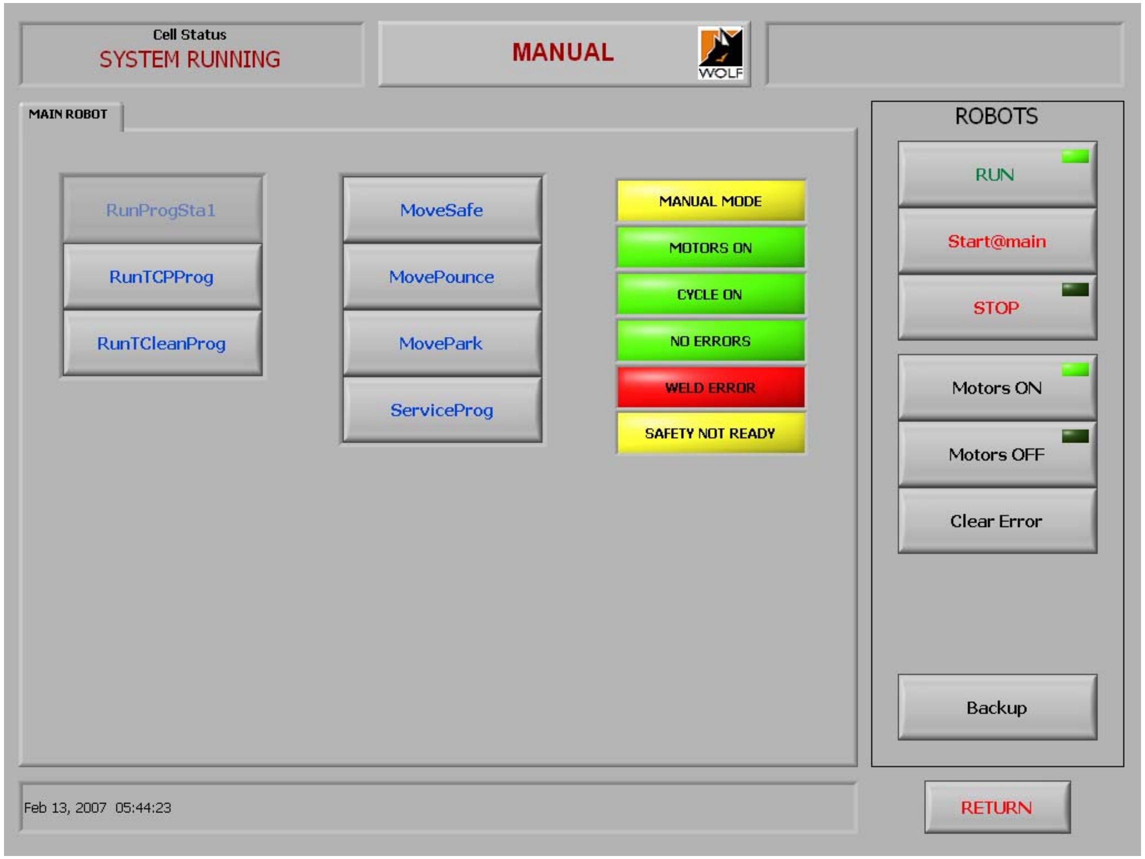
Intentionally Blank

Wolf Cell Controller (WCC)
Execute the Weld – 2 of 2



Wolf Cell Controller (WCC)
Execute the Weld – 1 of 2

Safety Switch	• Press inside button, exit cell, shut door, press **SAFETY RESET**	• Redundant safety so no one in cell while in AUTO mode. • BLUE light should come on.
ABB Controller	• Turn key to **AUTOMATIC** mode	
ABB Teach Pendant	• Press **OK** to clear warning message	• Must acknowledge change to AUTOMATIC mode.
WCC	• Press **PART SETUP** to define joint • Press **RUN** to begin robot program and enable motors • Press **OPERATION READY** to initiate weld setup	• **PART SETUP** → refer to other section of instructions. • **RUN** moves robot to the "SAFE" position. • **OP READY** moves robot to "POUNCE" position.
ABB Teach Pendant	• "Setup Weld?" → press **YES** *(robot moves to "Safe" position)* • Instruction screen → press **OK** *(robot moves to "Pounce" position)*	• Allows operator to define location of the joint that is to be welded by jogging the robot "near" the joint.
ABB Controller	•Turn key to **MANUAL** mode	• Robot must be in MANUAL mode to enable jogging.
Safety Switch	• Press **CLEAR REQUEST**	• Forces the system into a disabled mode before allowing operator entry.
ABB Teach Pendant	• Press and hold **ENABLING SWITCH** • Jog robot to *near* the joint • Press **START** to resume robot program • "Is this the correct CL starting position?" → **YES** or **NO** • Change Weld Offset screen → Change or Cancel • "Is this the correct weld offset position?" → **YES or NO** • "Dry Run?" → **YES** or **NO** • "Ready to Weld?" → Release the **ENABLING SWITCH,** exit cell	• Operator jogs robot close enough for ServoRobot seam tracker to register the joint. • Operator proceeds through Teach Pendant screens. • Operator must exit cell before acknowledging "Ready to Weld?" in order to switch back to AUTOMATIC mode.
Safety Switch	• Press inside button, exit cell, shut door, press **SAFETY RESET**	• Redundant safety so no one in cell while in AUTO mode. • BLUE light should come on.
ABB Controller	• Turn key to **AUTOMATIC** mode	
ABB Teach Pendant	• Press **OK** to clear warning message	• Must acknowledge change to AUTOMATIC mode.
WCC	• Press **OK** to clear the warning message. • Press **RUN** to start motors and start robot program	
ABB Teach Pendant	• "Ready to Weld?" → **YES**	• Weld executes

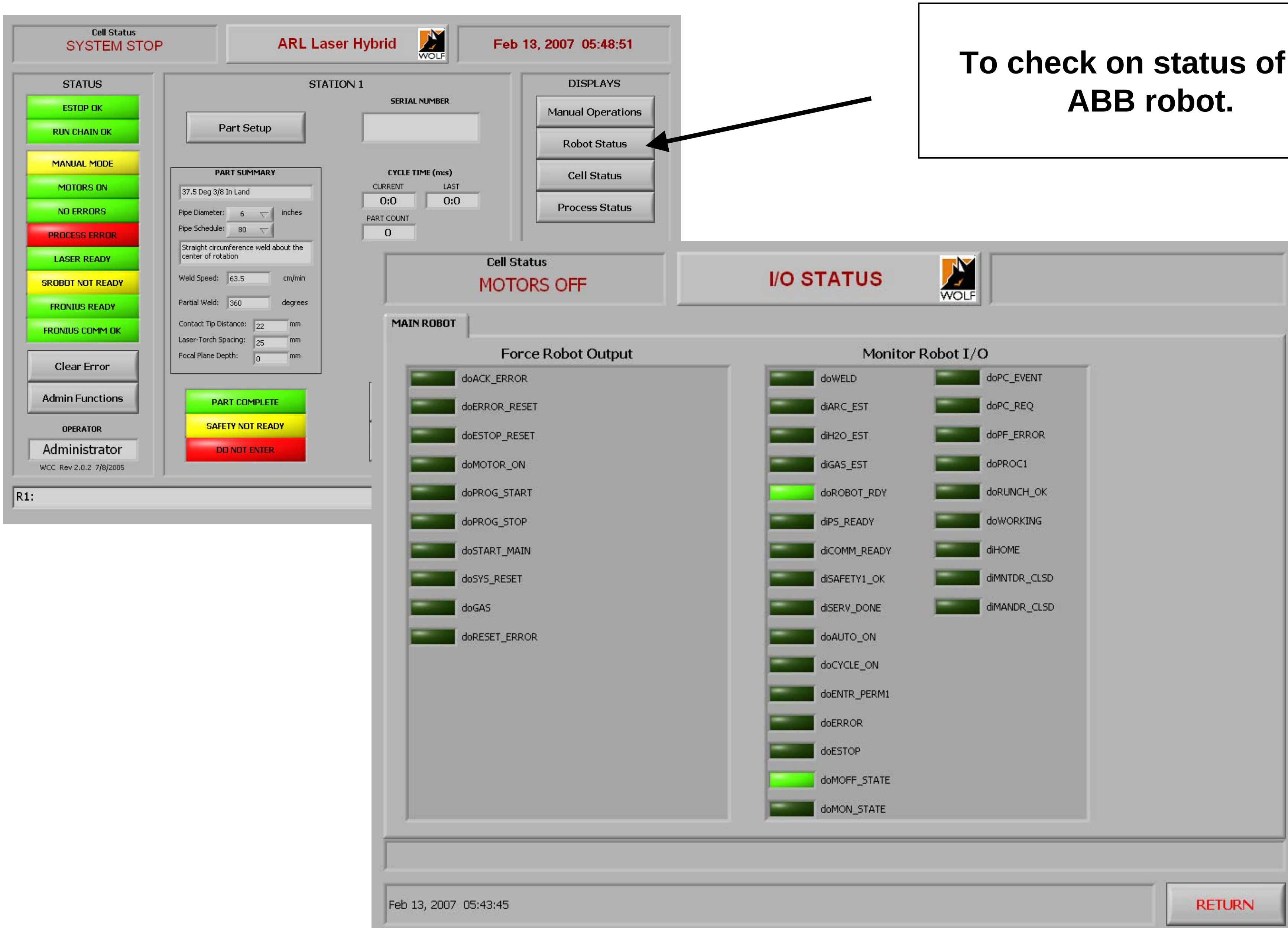


To manually force robot operations.

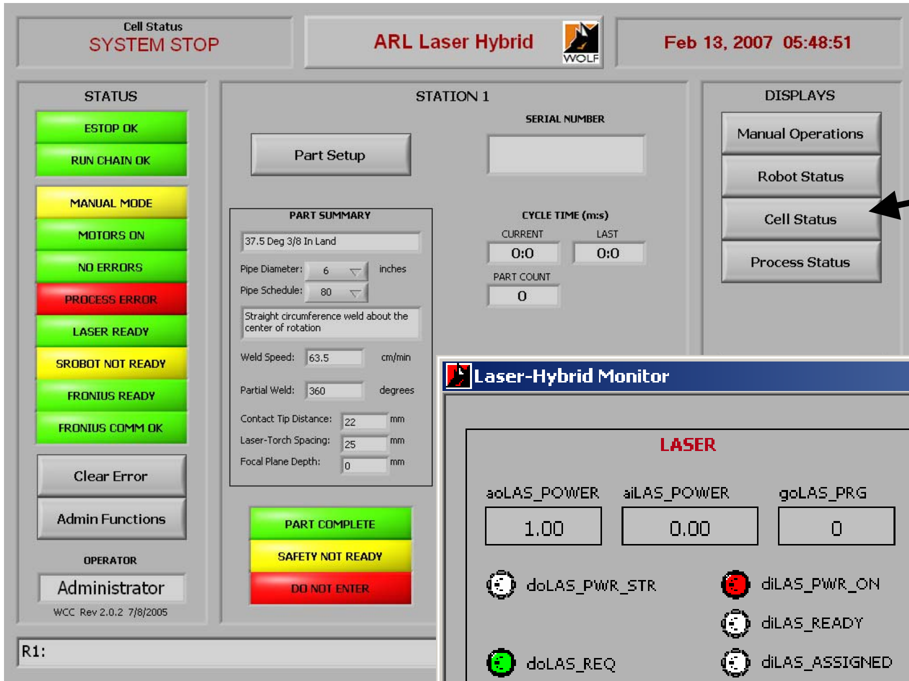
MoveSafe	Moves to “Safe” position (out of way of pipe).
MovePounce	Moves to “Pounce” position (above the pipe).
MovePark	Moves to “Park” position (out of way of pipe, closing the PARK switch).
Start@main	Forces the robot program to execute from the beginning (useful for restart after irregular stop, robot must be able to move directly to “Safe” position).
Motors ON	Turns on the robot motors to enable motion.
RUN	Begins execution of the robot program (necessary to use the WCC).

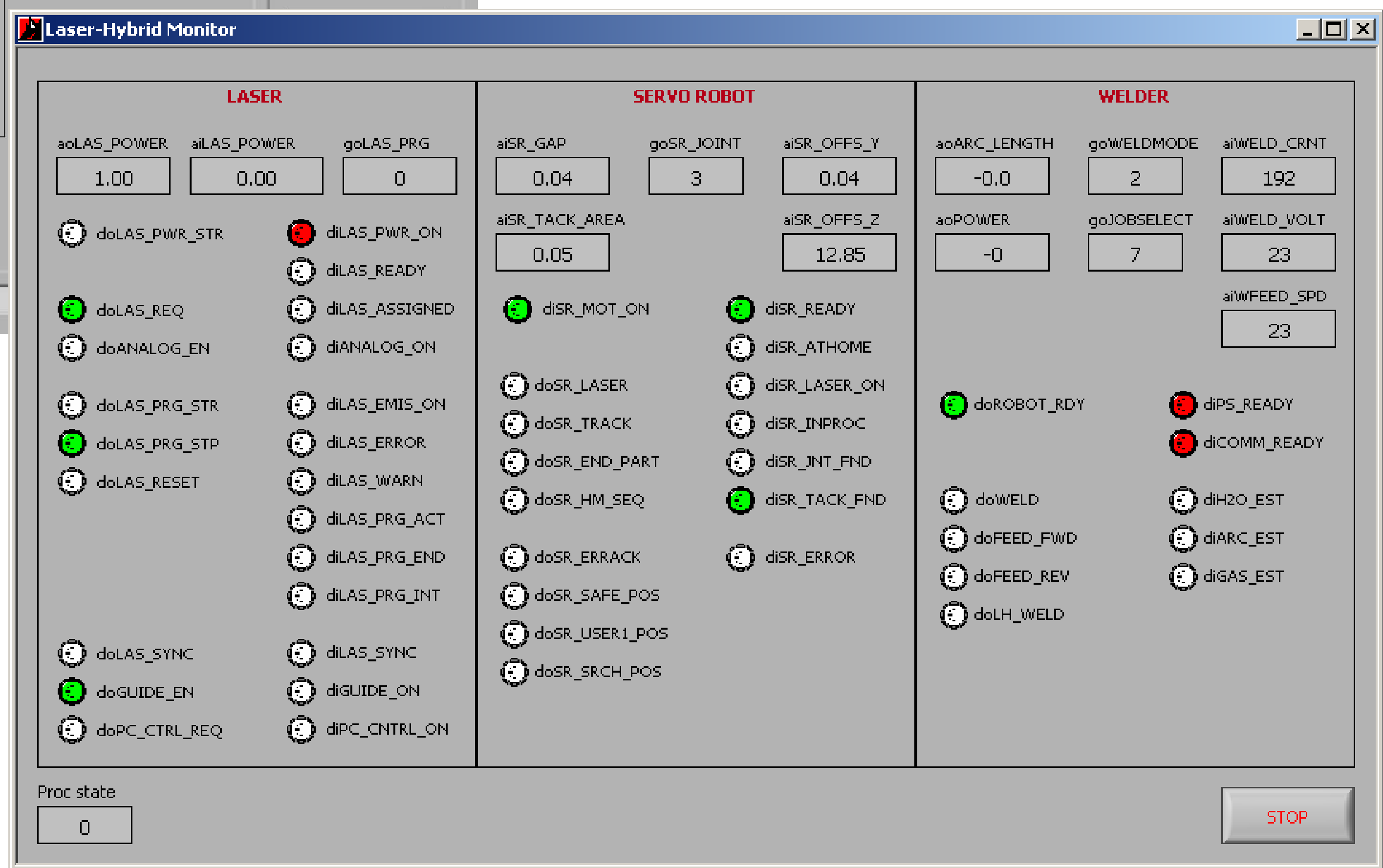
Wolf Cell Controller (WCC)
Robot I/O Status – 1 of 1

To check on status of the ABB robot.



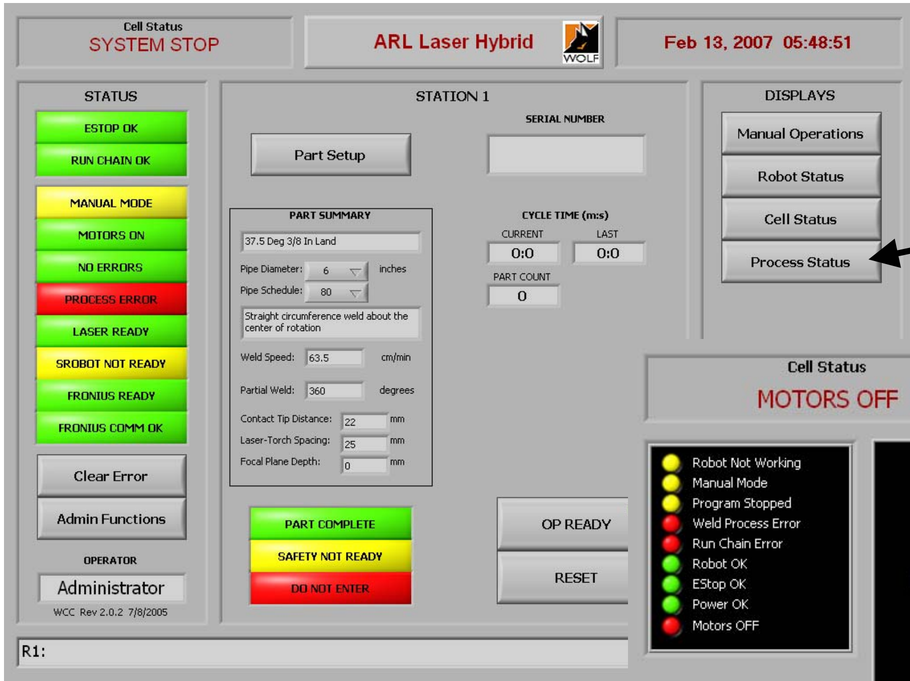
Wolf Cell Controller (WCC)
Cell Status – 1 of 1

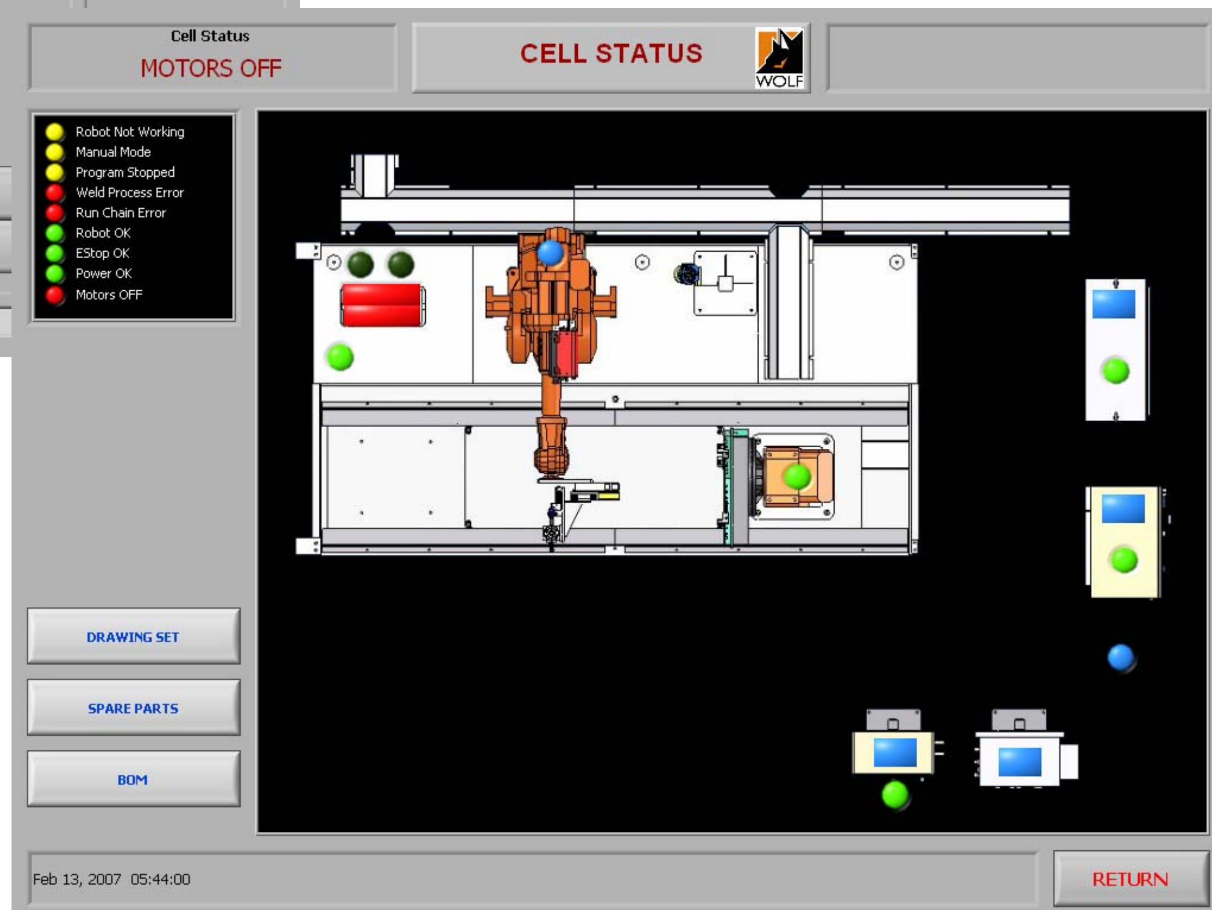




To check on status of the IPG laser, ServoRobot seam tracker, and Fronius welder.

Wolf Cell Controller (WCC)
Log In – 1 of 1





To check on status of the E-stop chain.

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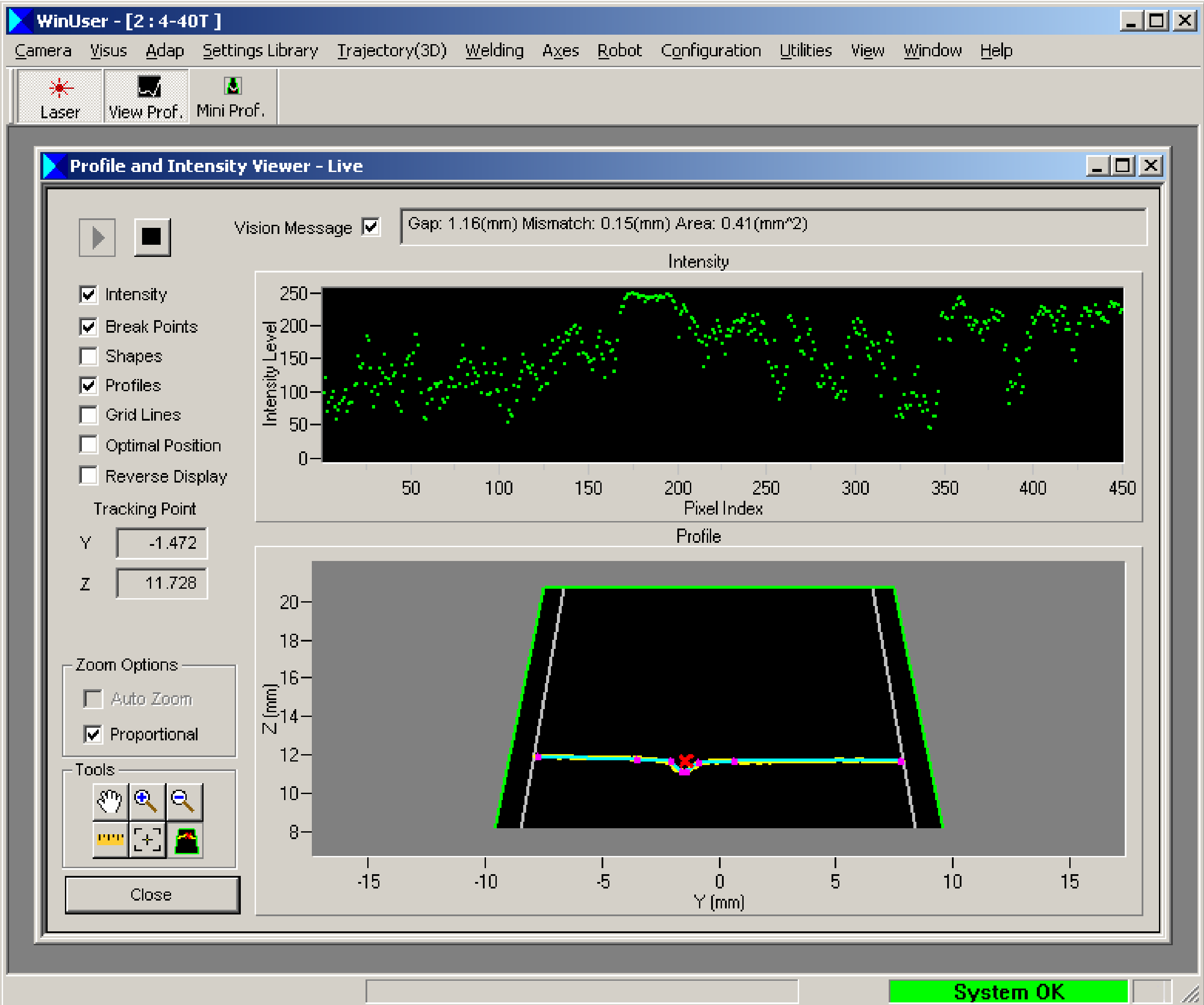
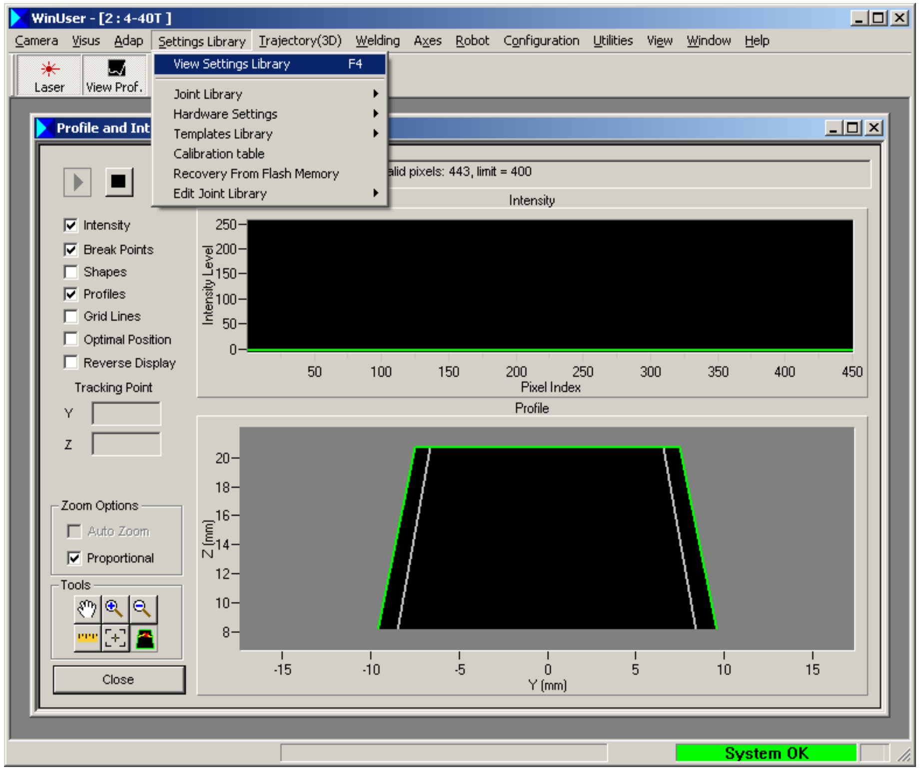
ServoRobot

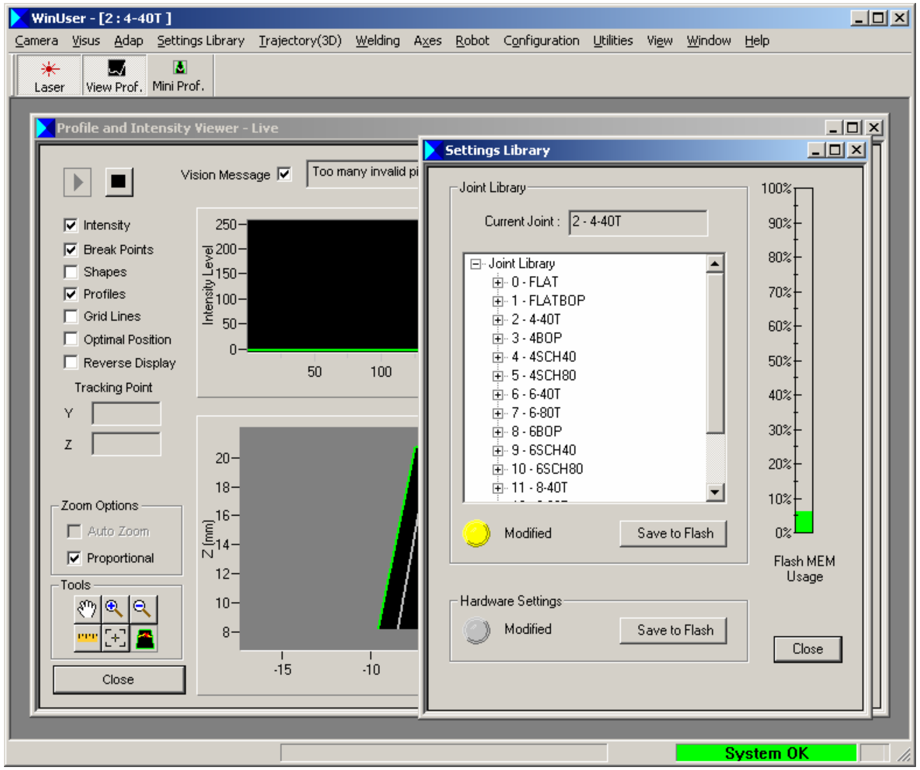
Seam Tracking System

ServoRobot
Main Screen – 1 of 1





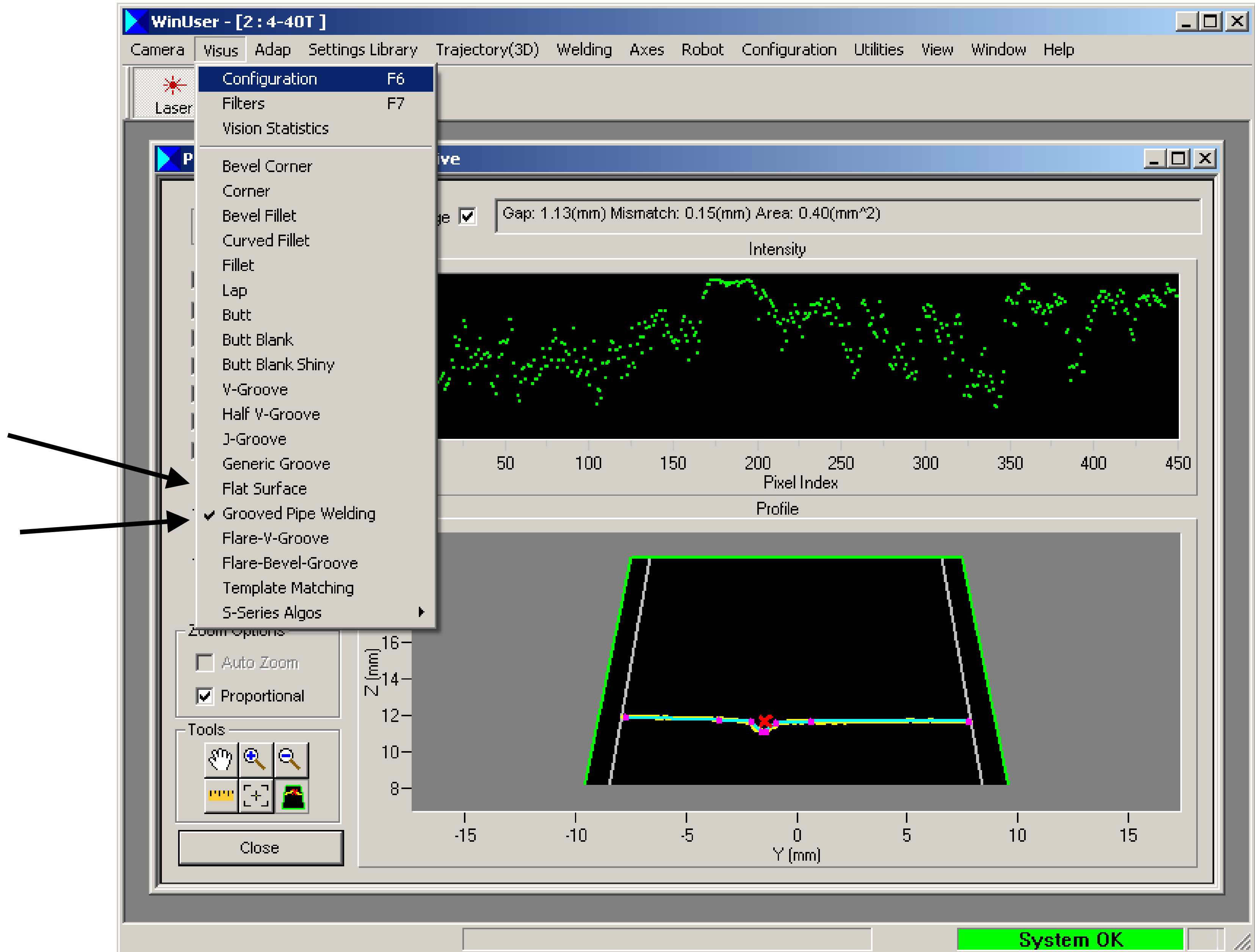
To select and define the ServoRobot Joint.



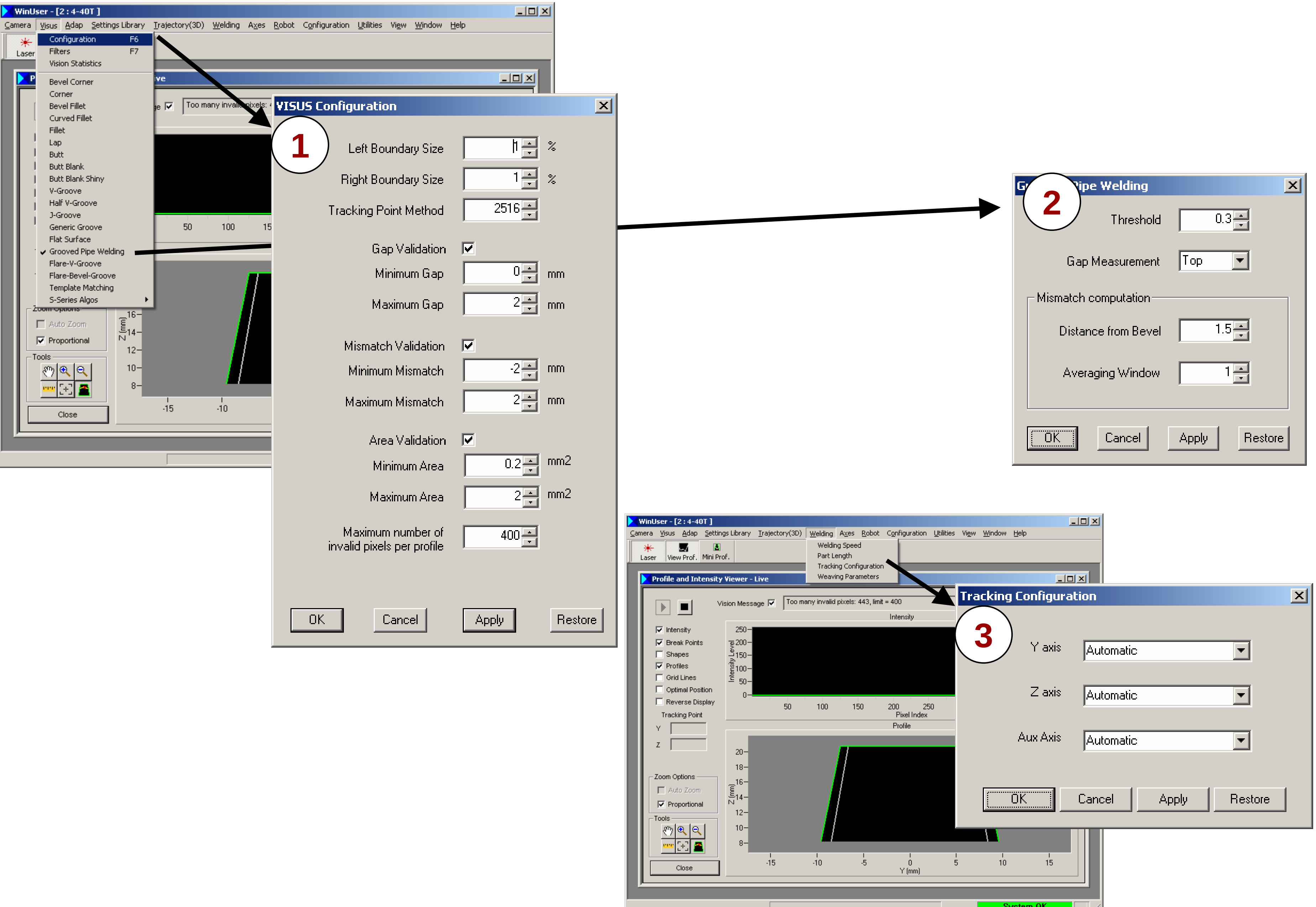
The ServoRobot Joint Number is specified as a Process Parameter in the WCC. Each joint contains information about how to track the joint:

- Joint type
  - Grooved Pipe Welding (V-groove) or
  - Flat Surface (no joint or bead-on-plate))
- Tracking point
- min/max Gap, Mismatch, Area
- Tracking configuration (which tracking axes are operational)
- Weld speed (use to set delay in motion)

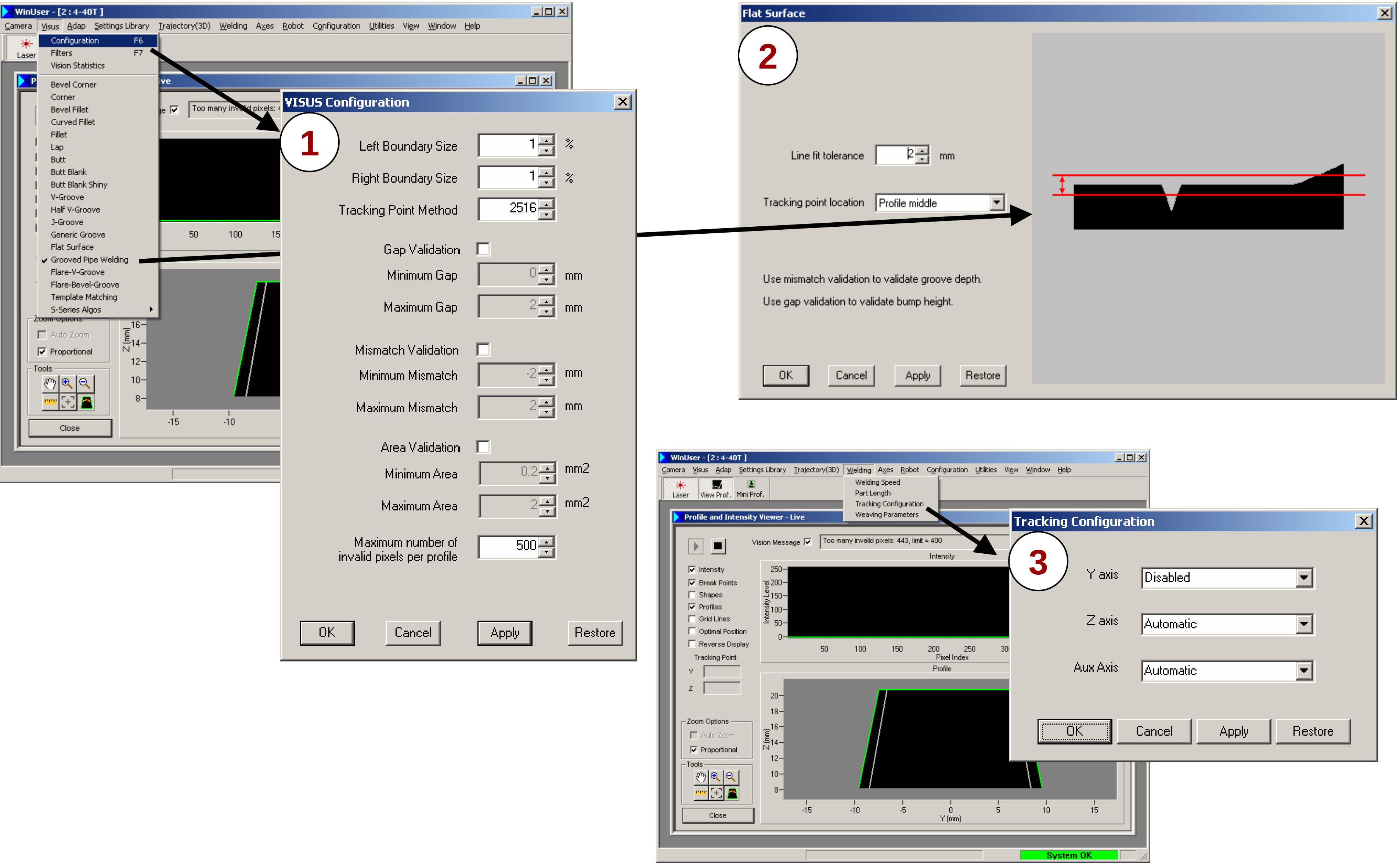
Defining the Joint – 2 of 5



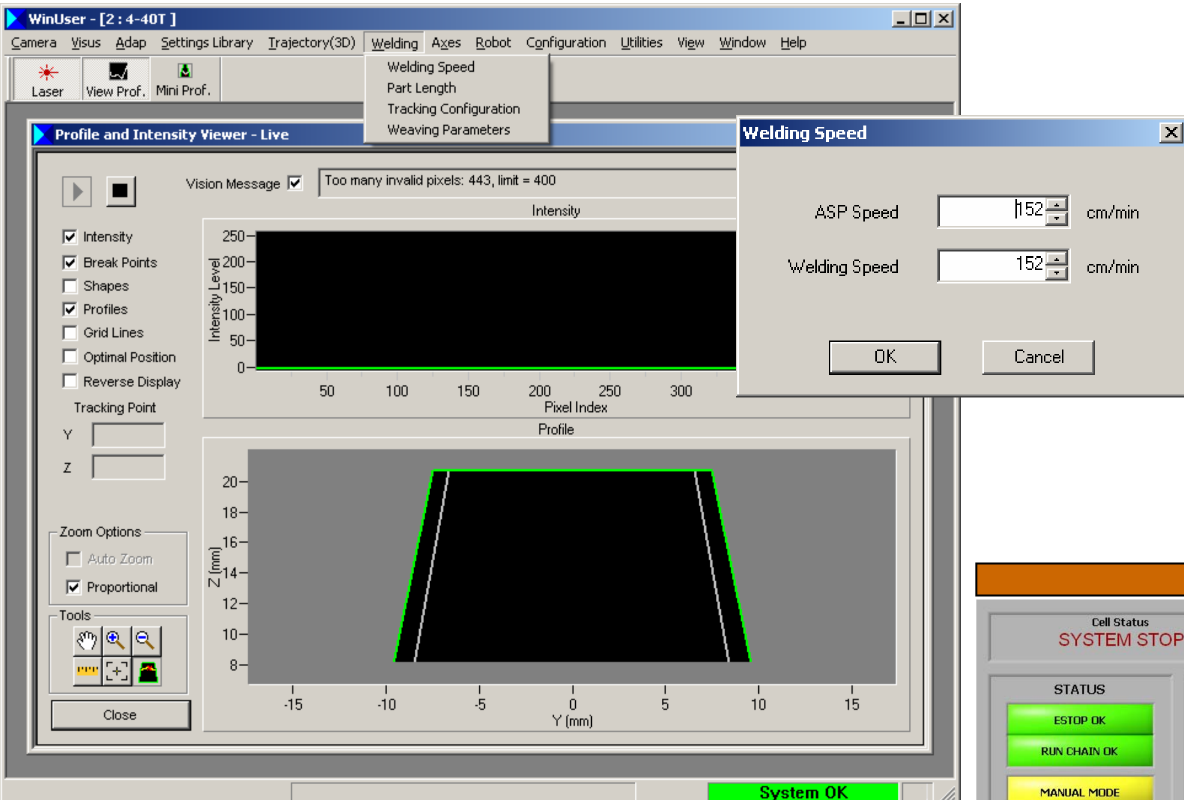
ServoRobot
Defining the Joint – 3 of 5 (Grooved Weld)

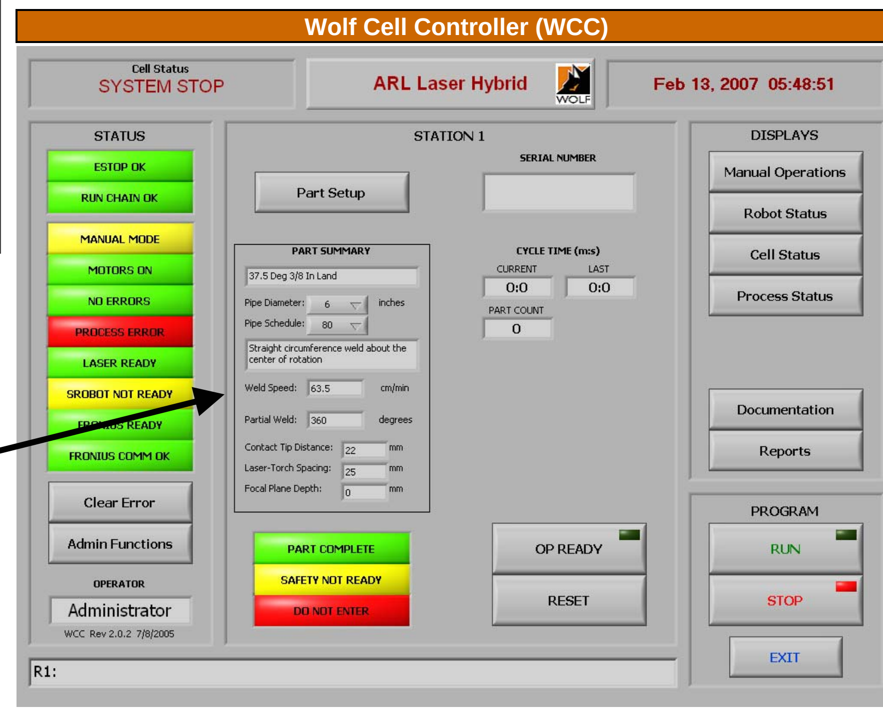


ServoRobot
Defining the Joint – 4 of 5 (Bead-On-Plate)



ServoRobot
Defining the Joint – 5 of 5 (Setting Weld Speed)





Can double-check the weld speed on the front panel of the WCC

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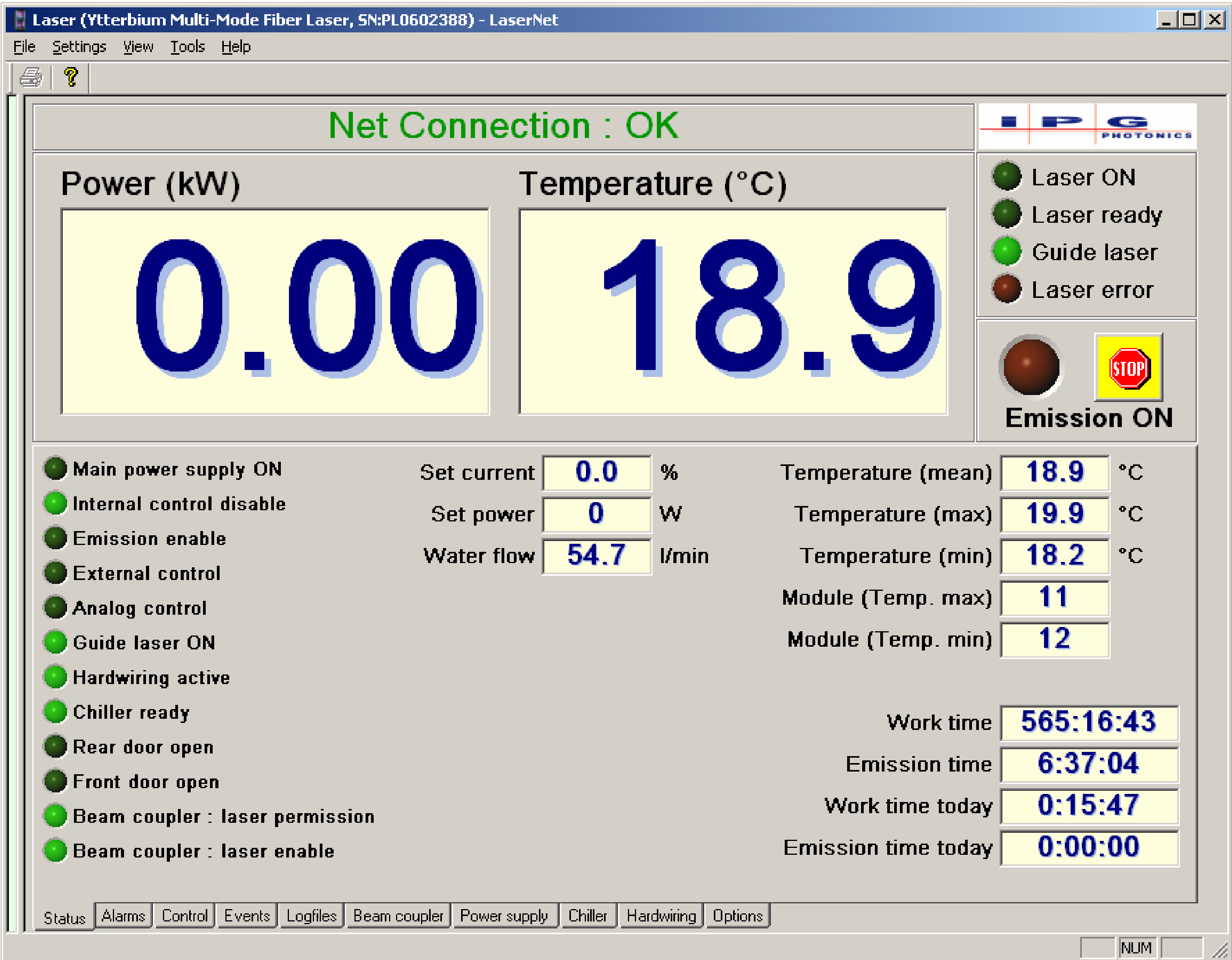
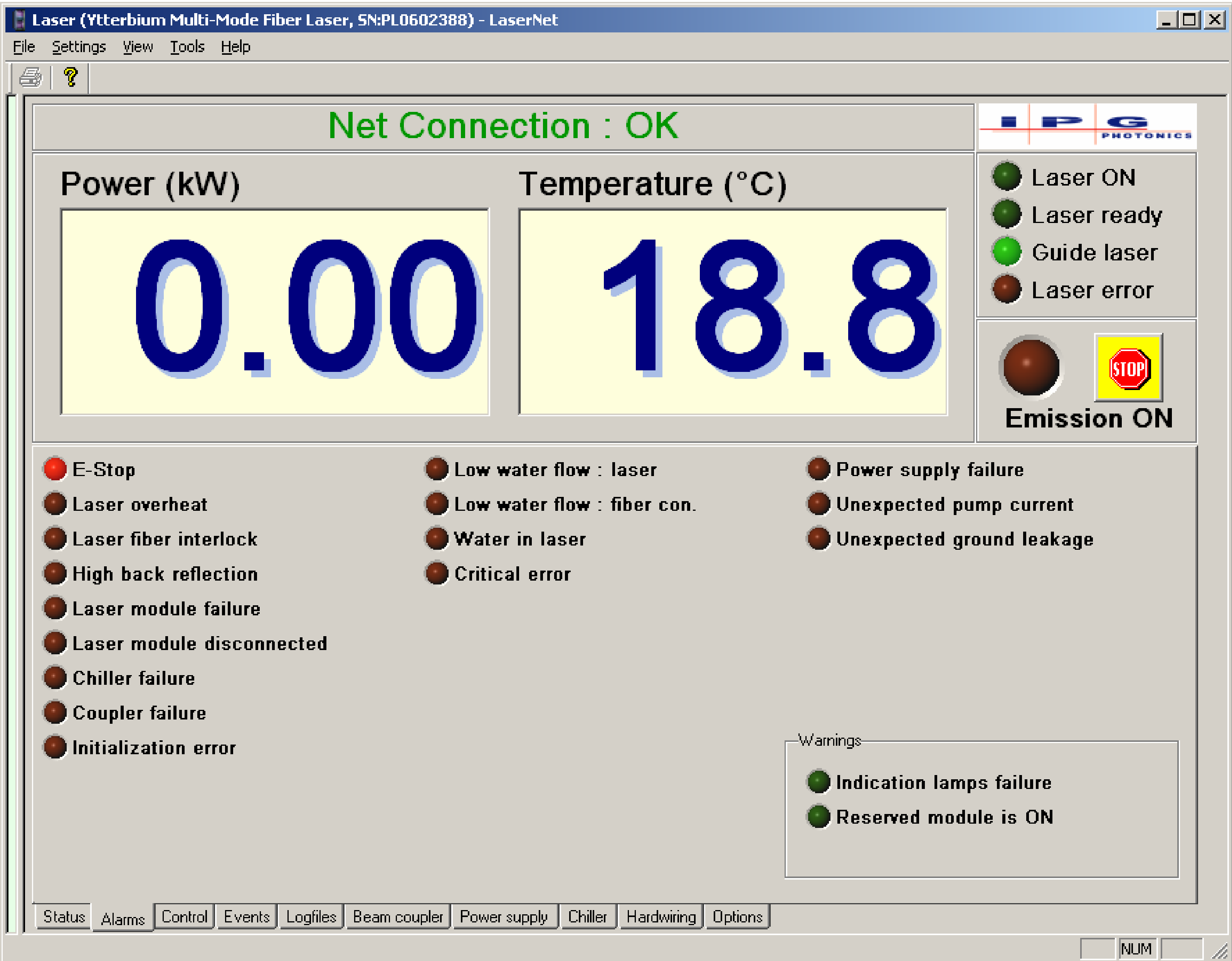
IPG

Laser System

IPG Laser
Main Screens – 1 of 2 (Status)



IPG Laser
Main Screens – 2 of 2 (Alarms)



APPENDIX C. NASSCO Reports

GENERAL DYNAMICS
NASSCO

03/23/07

Hybrid Pipe Welding System at NASSCO

PREPAIRED BY:
Juan Avalos
Randy Doerksen
Assistant Welding Engineer

APPROVED BY:
Michael J. Sullivan
Chief Welding Engineer

WELD ENGINEERING

GENERAL DYNAMICS
NASSCO

Hybrid Laser Robot arrives at NASSCO

WELD ENGINEERING

GENERAL DYNAMICS
NASSCO

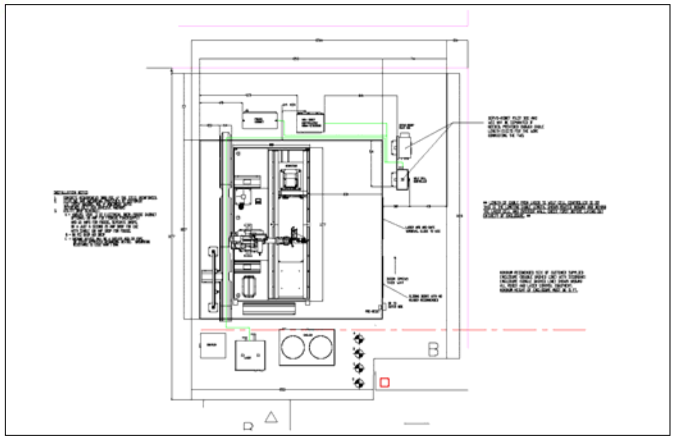
Robot being off loaded

WELD ENGINEERING

GENERAL DYNAMICS
NASSCO

Rotating Positioner

WELD ENGINEERING



Cell layout

WELD ENGINEERING

View from the out side of the cell.
Pipe Shop

WELD ENGINEERING

GENERAL DYNAMICS

NASSCO

ARL Penn State Robot

WELD ENGINEERING

GENERAL DYNAMICS

NASSCO

Crated and open Chiller and Laser

WELD ENGINEERING

GENERAL DYNAMICS
NASSCO

Wolf Cell Controller (WCC)

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GENERAL DYNAMICS
NASSCO

POSIOC
Robot controller

ABB
Cabinet

WELD ENGINEERING

GENERAL DYNAMICS
NASSCO

Bottles of Argon 100%, Compressed Air and 10% C02 / 90% Argon

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GENERAL DYNAMICS
NASSCO

View of the inter cell doors close

WELD ENGINEERING

GENERAL DYNAMICS
NASSCO

View of the inter cell
doors open

WELD ENGINEERING

GENERAL DYNAMICS
NASSCO

Work tables and pipe tacking area

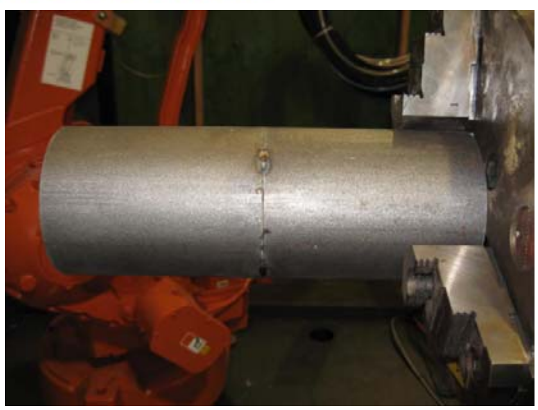
WELD ENGINEERING

GENERAL DYNAMICS
NASSCO

Operator teaches welding position

WELD ENGINEERING

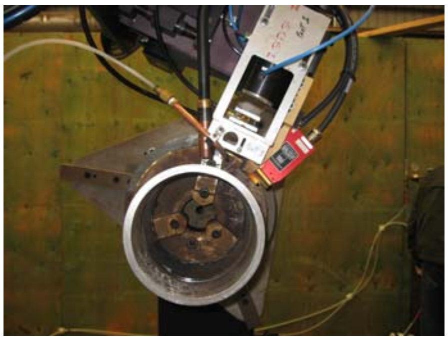
GENERAL DYNAMICS
NASSCO

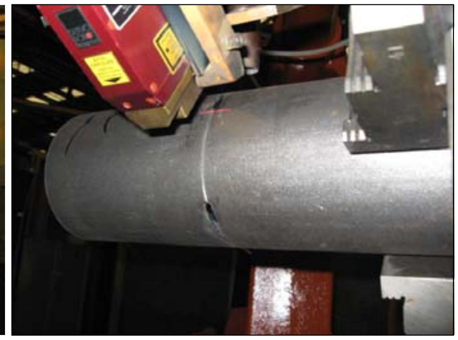


6” Pipe (Tacked)
in Positioner

WELD ENGINEERING

GENERAL DYNAMICS
NASSCO





Laser Tracker On

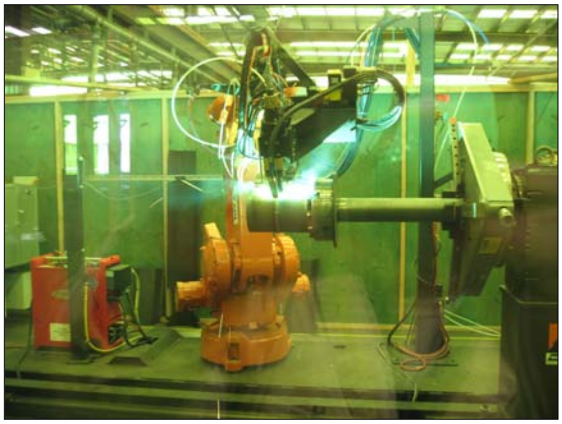
WELD ENGINEERING

GENERAL DYNAMICS
NASSCO

Inter-lock of secondary door

WELD ENGINEERING

GENERAL DYNAMICS
NASSCO



Robot Welding

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Test weld sample complete

WELD ENGINEERING

GENERAL DYNAMICS
NASSCO

Close up of the out side of the welded pipe

WELD ENGINEERING

GENERAL DYNAMICS
NASSCO

Close up of the inside of the welded pipe

WELD ENGINEERING

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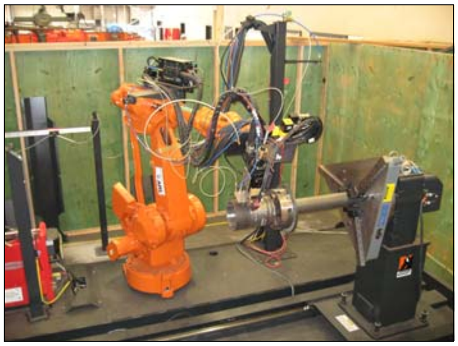
NASSCO

Welded test samples completed
4” sch. 40 / 4” sch. 80 / 6” sch. 40

WELD ENGINEERING

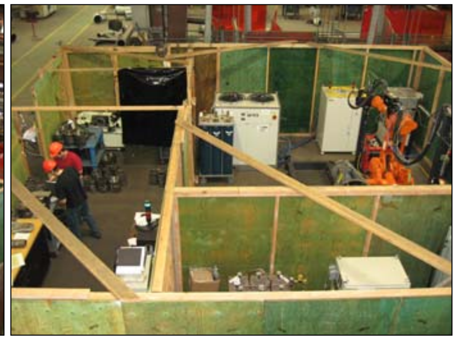
GENERAL DYNAMICS
NASSCO



Aerial Views

WELD ENGINEERING

GENERAL DYNAMICS



More Aerial Views

WELD ENGINEERING

GENERAL DYNAMICS

Welded samples

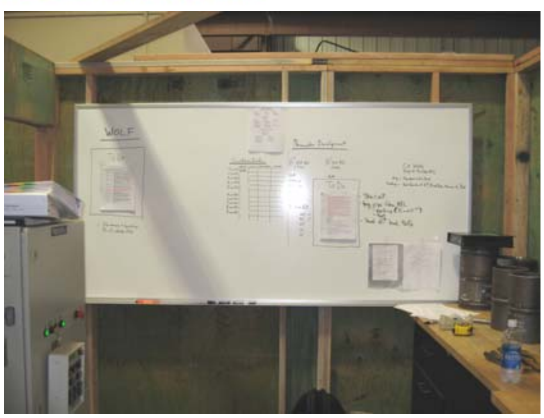
WELD ENGINEERING

GENERAL DYNAMICS
NASSCO

Actual 8” pipe welded in the pipe shop compared to Hybrid welding

WELD ENGINEERING

GENERAL DYNAMICS
NASSCO



To do board

Over 70 pipe samples welded to date

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GENERAL DYNAMICS
NASSCO


Tacked


Welded

Small production test was run with these 10 pipe samples

WELD ENGINEERING

GENERAL DYNAMICS
NASSCO

Small Production Test Run

Test No.	*Pipe Size*	*Pipe Sch.*	*Start Time*	*Load*	*Set up & Taught*	*Welded*
07-221	4”	40	0:00	32 sec.	5 min. 25 sec.	6 min. 35 sec.
07-222	6”	40	X	11 min. 05 sec.	14 min. 15 sec.	16 min 05 sec.
07-223	4”	80	X	18 min. 30 sec.	22 min. 55 sec.	24 min. 00 sec.
07-224	8”	40	X	25 min. 25 sec.	29 min. 35 sec.	30 min. 35 sec.
07-225	8”	80	X	33 min. 15 sec.	36 min. 55 sec.	38 min. 35 sec.
07-226	4”	40	X	39 min. 50 sec.	42 min. 40 sec.	44 min. 20 sec.
07-227	6”	40	X	46 min. 10 sec.	49 min. 35 sec.	50 min. 55 sec.
07-228	4”	80	X	52 min. 10 sec.	55 min. 10 sec.	57 min. 10 sec.
07-229	8”	40	X	58 min. 00 sec.	61 min. 10 sec.	62 min. 35 sec.
07-230	8”	80	X	64 min. 00 sec.	67 min. 05 sec.	68 min. 40 sec.
					TOTAL	68 min. 40 sec.

PROCEDURE:

“Load”
To load the test pipe onto the rotating positioner for welding.
Check cover glass to laser, wipe surface clean.
Off loading previous pipe from positioner.

“Set up & Taught”
Input set up data at the WCC including serial number.
Teach weld starting point.
Finish set up with pendant and WCC.

“Welded”
Weld the pipe
Inspect the weld

WELD ENGINEERING

GENERAL DYNAMICS

NASSCO

GENERAL DYNAMICS / NASSCO
2798 Harbor Drive
San Diego CA 92186-5278
(619) 544-3599 / Fax (619) 544-7516

PROCEDURE QUALIFICATION RECORD
(PQR) NP-11A1.1

Laser-GMA Hybrid
Base Material: Cfe Pipe
Filler Material:

THIS IS TO CERTIFY THAT THE PROCEDURE, AS LISTED ABOVE, HAS BEEN SATISFACTORILY QUALIFIED IN ACCORDANCE WITH THE REQUIREMENTS OF ABS 2006 RULES, AND THE SIGNATURES BELOW INDICATE APPROVAL OF THIS PROCEDURE.

PREPARED BY: Randy E Doerksen, Assistant Welding Engineer — DATE: March 22, 07

APPROVED BY: /s/ Michael J Sullivan, Manager of Accuracy Control and Chief Welding Engineer — DATE: March 22, 2007

APPROVED BY: Don Haydock, ABS, Engineer Materials Department — DATE: March 23 2007

WELD ENGINEERING

GENERAL DYNAMICS

NASSCO

GENERAL DYNAMICS / NASSCO
2798 Harbor Drive, San Diego CA
(619) 544-3599 / (619) 544-7516

PROCEDURE QUALIFICATION RECORD (PQR)

Procedure Qualification Record No. NP-11A1.1 Revision No. – Date 21, March 2007

WPS No. ______ Welding Procedure Qualification: √ A.B.S √ ASME ☐ Other

Robot: Wolf Robotics Integrator / ABB S4CPLUS M2000 Controller / ABB IRB4400/45 six axis robot

Positioner: Preston Eastin Model No. PC42B with ABB MTS2000

Laser: IPG Photonics Laser, Model YLR-7000 / Haas Weld Head

Weld head: Haas Weld Head

Seam Tracker: ServoRobot Seam Tracker (Model no. Pilot-LW with Rafal SSO-W

GMAW Power Supply: Fronius TPS5000

JOINTS (QW-402)

Joint Design (Root Opening)	Square Butt Joint
Bevel	1/32 inch for Seam Tracking
Root Gap	0 mm
Base Material Specifications / Grade	ASTM A 53
Pipe Schedule (Thickness) / Diameter	40 (0.280 inch) / 6 inch
Filler Metal Specification	AWS A5.18
Filler Metal Classification / Diameter	ER-70S-6 / 0.045 inch
Pipe Edge Preparation	Machined Joint
Preheat / Interpass	60° F / N / A

Details

LASER

Type	IPG Photonics, YLR 7000 Fiber Laser
Power	4.5 kW
Wavelength	1070 nm
Fiber Diameter	300 micron
Focal Length	200 mm
Free Aperture	48 mm
Focal Plan Depth	0 mm from plate surface
Plasma Suppression Gas	Argon at 50 scfh directed horizontally ~15 deg and ½ inch above pipe surface

Seam Tracker Technical Data (refer to ServoRobot manual)

Type	ServoRobot Pilot-LW with Rafal / SSO-W
Detector	Photosensitive Device
Light Source	Built-in 50 mW visible laser diode

WELD ENGINEERING

GENERAL DYNAMICS
NASSCO

Procedure Qualification Record No. NP-11AL1 Revision No. — Date 21, March 2007

TECHNIQUE

Laser to torch distance	25 mm
Laser Head Angle	0 deg relative to radius
Laser Position	35 mm ahead of TDC
Gun Angle	28 deg relative to radius (pushing, i.e. laser leading)
Contact Tip Distance (CTWD)	5/8 inch
Position of Pipe	0 deg to horizontal
Travel Speed	30 ipm along the surface of the pipe

Tack Welding Instructions: 1/2 to 1 inch length. Manual TIG autogenious. (4) tacks on pipe at 90 deg intervals

Weld Overlap Requirements: As below

Start of 1st Ramp	0.00 inch
End of 1st Ramp	0.25 inch
Start of 1st GMAW	1.25 inch
Start of 2nd Ramp	1.00 inch
End of 2nd Ramp	1.75 inch
End of 2nd GMAW	2.25 inch

(Reference Diagram in list of Attachments)

GMAW (Fronius TPS5000)

Welding Mode	Synergic Pulse
WFS	250 ipm
Fronius Job No.	11 (see table below)
Shielding Gas	Ar - 10% CO2
Gas Flow Rate	50 scfh
Orifice or Gas Cup Size	0.68 inch

WELD ENGINEERING

GENERAL DYNAMICS
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Procedure Qualification Record No. NP-11AL1 Revision No. — Date 21, March 2007

NASSCO Test I.D. No. 03-09 Welder E. Villa Badge Number 51929

Nondestructive Examinations conducted by: NASSCO, General Dynamics

Weld Macro Tests

Specimen No.	Results
#1	Accept
#2	Accept

Nondestructive Examinations conducted by: Gamma Tech Industries, Inc. Report No. 07-028-B (attached)

NDT Tests

Type	Results
V.T.	Accept
Radiograph	Accept

Destructive Examinations conducted by: Gamma Tech Industries, Inc. Report No. 07-028-1 (attached)

Guided-Bend Test

Specimen No.	Type of Bend	Mandrell Radius	Specimen Width	Specimen Thickness	Result
#1	Root Bend	0.560"	1.5"	0.280"	Accept
#2	Root Bend	0.560"	1.5"	0.280"	Accept
#3	Face Bend	0.560"	1.5"	0.280"	Accept
#4	Face Bend	0.560"	1.5"	0.280"	Accept

Tensile Test

Specimen No.	Width Inches	Thickness or Diameter	Square Inch Area	Ultimate Tensile Load-lb.	Ultimate Tensile Strength	Character of Fracture and Location	Results
TR-1	0.749	0.260	0.1947	14,600	74,987	Base Metal	Accept
TR-2	0.749	0.260	0.1947	14,360	73,754	Base Metal	Accept

WELD ENGINEERING

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Procedure Qualification Record No. NP-11A1.1 Revision No. --- Date 21, March 2007

TESTS CONDUCTED BY : NASSCO, General Dynamics

(2) Macro-Etch Weld Specimens

TESTS CONDUCTED BY : Gamma Tech Industries, Inc.

R.T. Inspection (ABS & ASME Boiler and Pressure Vessel Code, Section V Requirements)	GTI Job No 07-028-B
Reduced-section Tension Test, Pipe (ABS Rules)	GTI Job No 07-028-B
(2) Root and (2) Face Bend Tests (ABS Rules)	GTI Job No 07-028-B

We certify that the statements in this record are correct and that the test welds were prepared, welded and tested in accordance with ABS Rules 2006.

Date March 22, 2007

Prepared by: Randy Doerksen
Assistant Welding Engineer

* Test Reports are maintained on file by Welding Engineering.

NOTES:

WELD ENGINEERING

GENERAL DYNAMICS

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Procedure Qualification Record No. NP-11A1.1 Revision No. --- Date 21, March 2007

— ATTACHMENTS —

A. Test Documentation
- R.T. Inspection
- Mechanical Inspection (2)Transverse Tensiles (Photos)
  (4) Guided Side Bends (Photos)
- Photo-Macro of weld cross-section (Photos)

B. Base Material Certifications
- ASTM A 53/A Standard Specification for Pipe, Steel, Black and Hot Dipped Zinc Coated, Welded and Seamless

C. Certified Filler Metal Test Reports
- Super-Arc L-56 Electrode, ER70S-6 / AWS A5.18

D. Weld Overlap Requirements

WELD ENGINEERING

GENERAL DYNAMICS

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GAMMA TECH INDUSTRIES, INC.
3645 DALBERGIA STREET
SAN DIEGO, CALIFORNIA 92113-3812
Tel. (619) 231-3808 FAX (619) 231-3811

RADIOGRAPHIC WORK & INTERPRETATION RECORD

DATE: 14 MARCH 2007
CUSTOMER: NATIONAL STEEL AND SHIPBUILDING COMPANY
GTI JOB NO.: 07-028-B
PO #: VERBAL
JOB DESCRIPTION: RADIOGRAPHIC INSPECTION OF LASER WELDED PROCEDURE QUALIFICATION PIPE

RADIOGRAPHIC OPERATIONS PROCEDURE:
SOURCE OF RADIATION: NORELCO/PHILLIPS 250 Kv/10Ma FOCAL SIZE: 4mm SFD: 54" FOCAL ANGLE: 90°
FILM TYPE: SINGLE LOADED KODAK "AA-400" INTENSIFYING SCREENS: 0.005" Pb FRONT & BACK
FILM VIEWING: SINGLE PENETRAMETER: ASTM #10 PENE LOCATION: SOURCE SIDE
SENSITIVITY LEVEL: 2-4T EXPOSURE TIME: 35 SECONDS MAT'L THICKNESS: Tm = 0.280" Ts = 0.340"

RADIOGRAPHIC PROCEDURE SPECIFICATION:
ABS GUIDE FOR NDT OF HULL WELDS & ASME BOILER & PRESSURE VESSEL CODE, SECTION V

RADIOGRAPHIC ACCEPTANCE STANDARD:
ABS GUIDE FOR NDT OF HULL WELDS (CLASS-A) & MIL-STD-2035A (CLASS-1)
(NOTE: TOTAL AREA OF POROSITY PER INCH OF WELD MAY BE EQUAL TO 1% OF MATERIAL THICKNESS)

WELDING INFORMATION
WELDOR: MIKE SULLIVAN IDENTIFICATION: ___ WPS #: SP-11A1.1
WELD PROCESS: LASER / GMAW BASE MATERIAL: 6" SCH 40 CSE PIPE FILLER METAL: ER70S-6

IDENTIFICATION	VIEW	WELD LENGTH	ACCEPT	REJECT	DEFECT TYPE - DEFECT LOCATION - REMARKS
IGR QUAL PIPE TEST #9 BUTT WELD	21-0-4	5"	XX		ACCEPTABLE POROSITY
	3-8	5"	XX		ACCEPTABLE POROSITY
	6-11	5"	XX		10 PORES @ 0.030" DIA = 0.007 Sq In **(TOTAL POROSITY AREA ALLOWED IS 0.014 Sq In PER 5" WELD LENGTH)**
	10-15	5"	XX		20 PORES ≤1/64" (PORES ≤ 1/64" SHALL BE DISREGARDED) 4 PORES @ 0.030" DIA = 0.0028 Sq In
	14-18	5"	XX		17 PORES ≤1/64" (PORES ≤ 1/64" SHALL BE DISREGARDED) 12 PORES @ 0.030" DIA = 0.0085 Sq In
	17-0	5"	XX		14 PORES ≤1/64" (PORES ≤ 1/64" SHALL BE DISREGARDED) 7 PORES @ 0.030" DIA = 0.0049 Sq In

DEFECT NOMENCLATURE
IB - INSUFFICIENT BUILD-UP
ER - EXCESSIVE REINFORCEMENT
CC - CRATER CRACK
IP - LACK OF PENETRATION
P - POROSITY
C - CRACK
CVR - CONCAVE ROOT SURFACE
CXR - CONVEX ROOT SURFACE
LF - LACK OF FUSION
S - SLAG
ML - MISALIGNMENT
UC - UNDERCUT
RU - ROOT UNDERCUT
BT - BURN THROUGH
MT - MELT THRU

RADIOGRAPHER: ______
JIM HAM - ASNT LEVEL III #19720 / AWS CWI #82052041

INTERPRETER: ______
JIM HAM - ASNT LEVEL III #19720 / AWS CWI #82052041

AWS QC-1 CWI

WELD ENGINEERING

GENERAL DYNAMICS

NASSCO

GAMMA TECH INDUSTRIES, INC.
3645 DALBERGIA STREET
SAN DIEGO, CALIFORNIA 92113-3812
Tel. (619) 231-3808 FAX (619) 231-3811

MECHANICAL TEST REPORT
WELD PROCEDURE QUALIFICATION

DATE: 19 MARCH 2007
GTI JOB #: 07-028-J

CUSTOMER: NATIONAL STEEL & SHIPBUILDING COMPANY

WELD PROCESS: LASER / GMAW WELDING POSITION: ______

JOINT DESIGN: SQUARE BUTT JOINT

BASE MATERIAL: 6" Sch 40 (0.280" WALL) ASTM A-53B PIPE

FILLER MATERIAL: ER70S-6 TEST IDENTIFICATION NUMBER: #9

TENSILE TESTING

TEST #	DIMENSIONS INCHES	AREA Sq In	TENSILE LOAD POUNDS	TENSILE STRENGTH PSI	FAILURE SITE	RESULTS
TR-1	0.260 x 0.749	0.1947	14,600	74,987	BASE METAL	ACCEPT
TR-2	0.260 x 0.749	0.1947	14,360	73,754	BASE METAL	ACCEPT

GUIDED BEND TESTING

BEND TYPE & ID	MANDREL RADIUS	SPECIMEN WIDTH	SPECIMEN THICKNESS	RESULTS
ROOT BEND #1	0.560"	1.5"	0.280"	ACCEPT
ROOT BEND #2	0.560"	1.5"	0.280"	ACCEPT
FACE BEND #3	0.560"	1.5"	0.280"	ACCEPT
FACE BEND #4	0.560"	1.5"	0.280"	ACCEPT

THE ABOVE TESTS WERE PERFORMED IN ACCORDANCE WITH ABS RULE REQUIREMENTS FOR MATERIALS AND WELDING, 2006 - PART 2 & U.S. NAVY TECHNICAL PUBLICATION S9074-AQ-GIB-010/248.

INSPECTOR: ______
JIM HAM - ASNT LEVEL III #19720 / AWS CWI #82052041

WELD ENGINEERING

GENERAL DYNAMICS

NASSCO

Procedure Qualification Record No. NP-11A1.1 Revision No. — Date 21 March 2007

FACE BENDS

ROOT BENDS

TRANSVERSE TENSILES (2)

WELD MACRO-ETCH

WELD ENGINEERING

GENERAL DYNAMICS

NASSCO

TABLE 2 Tensile Requirements

	Type F	Types E and S	
	Open-Hearth, Basic Oxygen, or Electric-Furnace, Grade A	Grade A	Grade B
Tensile strength, min, psi [MPa]	48 000 [330]	48 000 [330]	60 000 [415]
Yield strength, min, psi, [MPa]	30 000 [205]	30 000 [205]	35 000 [240]
Elongation in 2 in. [50 mm]	A,B	A,B	A,B

A The minimum elongation in 2 in. [50 mm] shall be that determined by the following equation:

$$e = 625\,000\,[1940]\,A^{0.2}/U^{0.9}$$

where:

e = minimum elongation in 2 in. [50 mm] in percent rounded to the nearest percent,

A = cross-sectional area of the tension specimen, rounded to the nearest 0.01 in.² [1 mm²], based on the specified outside diameter or the nominal specimen width and specified wall thickness. If the area calculated is equal to or greater than 0.75 in.² [500 mm²], then the value 0.75 in.² [500 mm²] shall be used, and

U = specified tensile strength, psi [MPa].

B See Table X4.1 or Table X4.2, whichever is applicable, for minimum elongation values for various size tension specimens and grades.

chemical composition in Table 1 and the chemical analysis shall be in accordance with Test Methods, Practices, and Terminology A 751.

6. Product Analysis

6.1 The purchaser is permitted to perform an analysis of two pipes from each lot of 500 lengths, or fraction thereof. Samples for chemical analysis, except for spectrographic analysis, shall be taken in accordance with Practice E 1806. The chemical composition thus determined shall conform to the requirements specified in Table 1.

6.2 If the analysis of either pipe does not conform to the requirements specified in Table 1, analyses shall be made on additional pipes of double the original number from the same lot, each of which shall conform to the requirements specified.

7. Tensile Requirements

7.1 The material shall conform to the requirements as to tensile properties prescribed in Table 2.

7.2 The yield strength corresponding to a permanent offset of 0.2 % of the gage length of the specimen or to a total extension of 0.5 % of the gage length under load shall be determined.

7.3 The test specimen taken across the weld shall show a tensile strength not less than the minimum tensile strength specified for the grade of pipe ordered. This test will not be required for pipe under NPS 8 [DN 200].

7.4 Transverse tension test specimens for electric-welded pipe NPS 8 [DN 200] and larger shall be taken opposite the weld. All transverse test specimens shall be approximately 1½ in. [40 mm] wide in the gage length, and shall represent the full wall thickness of the pipe from which the specimen was cut. This test is required for NPS 8 [DN 200] and larger.

8. Bending Requirements

8.1 For pipe NPS 2 [DN 50] and under, a sufficient length of pipe shall be capable of being bent cold through 90° around a cylindrical mandrel, the diameter of which is twelve times the outside diameter of the pipe, without developing cracks at any portion and without opening the weld.

8.2 When ordered for close coiling, the pipe shall stand being bent cold through 180° around a cylindrical mandrel, the diameter of which is eight times the outside diameter of the pipe, without failure.

8.3 Double-extra-strong pipe over NPS 1¼ [DN 32] need not be subjected to the bend test.

9. Flattening Test

9.1 The flattening test shall be made on pipe over NPS 2 [DN 50] with all thicknesses extra strong and lighter.

9.2 *Seamless Pipe:*

9.2.1 For seamless pipe, a test specimen at least 2 ½ in. [60 mm] in length shall be flattened cold between parallel plates in two steps. During the first step, which is a test for ductility, no cracks or breaks on the inside, outside, or end surfaces, except as provided for in 9.7, shall occur until the distance between the plates is less than the value of H calculated as follows:

$$H = (1 + e)t/(e + t/D)$$

where:

H = distance between flattening plates, in. [mm] (Note 4),

e = deformation per unit length (constant for a given grade of steel, 0.09 for Grade A, and 0.07 for Grade B),

t = nominal wall thickness, in. [mm], and

D = specified outside diameter, in. [mm]

9.2.2 During the second step, which is a test for soundness, the flattening shall be continued until the test specimen breaks or the opposite sides of the pipe meet. Evidence of laminated or unsound material that is revealed during the entire flattening test shall be cause for rejection.

NOTE 4—The H values have been calculated for standard and extra-heavy weight sizes from NPS 2½ to NPS 24 [DN 65 to DN 600], inclusive, and are shown in Table X2.1.

9.3 *Electric-Resistance-Welded Pipe*— A test specimen at least 4 in. [100 mm] in length shall be flattened cold between parallel plates in three steps, with the weld located either 0° or 90° from the line of direction of force as required in 9.3.1 or 9.3.2, whichever is applicable. During the first step, which is a test for ductility of the weld, no cracks or breaks on the inside or outside surfaces at the weld shall occur until the distance between the plates is less than two thirds of the specified diameter of the pipe. As a second step, the flattening shall be continued as a test for ductility away from the weld. During the second step, no cracks or breaks on the inside or outside surfaces away from the weld, except as provided for in 9.7, shall occur until the distance between the plates is less than one third of the specified outside diameter of the pipe but is not less than five times the wall thickness of the pipe. During the third step, which is a test for soundness, the flattening shall be continued until the test specimen breaks or the opposite walls of the pipe meet. Evidence of laminated or unsound material or

WELD ENGINEERING

GENERAL DYNAMICS
NASSCO

The Lincoln Electric Company
22801 St. Clair Avenue
Cleveland, Ohio 44117-1199

CERTIFICATE OF CONFORMANCE
(APPLIES ONLY TO U.S. PRODUCTS)
SUPPLIED TO:
Order No.:
Production Code No.:
Size:

LINCOLN ELECTRIC

Product	Super Arc® L-56 Electrode
Classification	ER70S-6
Specification	AWS A5.18-2001, ASME SFA-5.18
Date Completed	July 26, 2002

[1Year]

This is to certify that the product named above and supplied on the referenced order number is of the same classification, manufacturing process, and material requirements as the material which was used for the test that was concluded on the date shown, the results of which are shown below. All tests required by the specifications shown for classification were performed at that time and the material tested met all requirements. It was manufactured and supplied according to the Quality System Program of the Lincoln Electric Company, Cleveland, Ohio, U.S.A., which meets the requirements of ISO9001, NCA3800, ANSI/AWS A5.01, JIS Z9002, and other specification and Military requirements, as applicable. The Quality System Program has been approved by ASME, ABS, and VdTUV.

Operating Settings

	.045	1/16
Wire Feed Speed (in/min)	450	320
Voltage (volts)	29	27
Current (amps) DC+	280	320
Shielding Gas	CO2	CO2

	.045	1/16
Electrical Stickout (in.)	3/4	3/4
Passes/Layers	13/6	13/6
Preheat Temp (°F)	70	70
Interpass Temp (°F)	325	300

Mechanical Properties of the weld deposit (in the as-welded condition) and Chemical Analyses of the electrode and weld deposit were as follows

	AWS/ASME REQUIREMENTS	Deposit .045	Deposit 1/16
Tensile Strength (psi)	70,000 min	83,100	83,700
Yield Strength (psi)	58,000 min	66,400	66,300
Elongation (%)	22 min.	28	28
Hardness, Rockwell B	Not Required	88	89
Impact Properties (Charpy V-notch), ft-lbs @ -20°F	20 min.	47 (44, 46, 50)	43 (28, 47, 54)

(%)	REQUIREMENTS	Electrode Analysis .045	Electrode Analysis 1/16	REQUIREMENTS	Deposit .045	Deposit 1/16
C	0.06 - 0.15	0.08	0.10	Not Required	0.08	0.10
Mn	1.40 - 1.85	1.49	1.42	Not Required	1.20	1.15
Si	0.80 - 1.15	0.97	0.84	Not Required	0.70	0.67
S	0.035 max	0.006	0.006	Not Required	0.006	0.007
P	0.025 max	0.011	0.011	Not Required	0.011	0.011
Ni	0.15 max	0.01	0.00	Not Required	0.01	0.01
Cr	0.15 max	0.03	0.01	Not Required	0.02	0.01
Mo	0.15 max	0.00	0.00	Not Required	0.00	0.00
V	0.03 max	0.00	0.00	Not Required	0.00	0.00
Cu (Total)	0.50 max	0.22	0.16	Not Required	0.18	0.15

Radiographic Test: Met requirements. Test assembly constructed of ASTM A36 steel.
The electrode diameter required to be tested for this classification is either .045" or 1/16". The .025", .030", .035", .052", and 1/16" sizes will also meet these requirements.

Diffusible Hydrogen, mL/100g of EIP (AWS A4.3-93)

Size (in.)	Results	Abs. Humidity (gr/lb)	
0.045	1.1	28	100% CO2

MICHAEL J. MORLOCK, CERTIFICATION SUPERVISOR

DAVID A. FINK, MANAGER, MATURE PRODUCTS, CONSUMABLE R & D DEPARTMENT

Cert. No. 10560

LINCOLN WIRE

Super Arc L-56

ER 70S-6 / Dia. .045

WELD ENGINEERING

GENERAL DYNAMICS
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SuperArc L-56 and SuperGlide S6 AWS ER70S-6

"Partnering with Lincoln Electric has resulted in very significant cost savings in our welding-related operations."

James MacLellan
The Holland Binkley Company
Warrinton, Missouri

SuperArc L-56 and SuperGlide S6

SuperArc L-56 and SuperGlide S6 offer improved mechanical properties, bead appearance and higher strength when a higher alloy content (manganese and silicon) is required. These wires are low carbon, high manganese, and very high silicon. SuperArc L-56 is a copper coated wire, SuperGlide S6 is bare wire.

AWS Electrode Composition Requirements
%C .06-.15, %Mn 1.40-1.85, %Si .80-1.15, %S .035, %P .025, %Cu .50
Note: Single values are maximum.

Typical Shielding Gases
100% CO_2, 75-95% Ar/Balance CO_2, 95-98% Ar/Balance O_2

Diameters
.025", .030", .035, .040", .045, .052, 1/16 in.
(0.6", 0.8", 0.9, 1.0", 1.1, 1.3, 1.6 mm)
* L-56 only

MECHANICAL PROPERTIES

Wire Type	Test Conditions	Tensile Strength psi (MPa)	Yield Strength psi (MPa)	Elongation (%)	Charpy V-Notch, ft-lbs (J) @ 0°F (-18°C)	@ -20°F (-29°C)	@ -40°F (-40°C)
SuperArc L-56, SuperGlide S6	REQUIREMENTS						
	ER70S-6 per AWS A5.18 AW with CO_2	70,000 min. (483)	58,000 min. (400)	22 min.	Not Specified	20 min. (27)	Not Specified
	MIL-70S-6 per MIL-E-23765/1 AW with CO_2 and 98Ar/2O_2	70,000 min. (483)	55,000 - 80,000 (379 - 552)	22 min.	Not Specified	Not Specified	Not Specified
	MIL-70S-6 per MIL-E-23765/1 SR with CO_2 and 98Ar/2O_2	70,000 min. (483)	52,000 min. (358)	26 min.	Not Specified	20 min. (27)	Not Specified
	TEST RESULTS						
	AW with CO_2	81,800 (564)	67,300 (464)	29	45 (61)	40 (54)	27 (37)
	SR with CO_2	74,200 (512)	56,600 (390)	29	85 (115)	70 (95)	50 (68)
	SR with CO_2	77,800 (536)	60,800 (420)	31		88 (119)	—
	AW with 75Ar/25CO_2	85,000 (586)	74,700 (515)	28	88 (119)	80 (108)	70 (95)
	SR with 75Ar/25CO_2	78,000 (538)	60,400 (416)	31	110 (149)	103 (140)	90 (122)
	AW with 90Ar/10CO_2	85,200 (587)	71,000 (489)	22	160 (217)	145 (196)	140 (190)
	SR with 90Ar/10CO_2	79,200 (546)	64,200 (443)	30	160 (217)	135 (183)	115 (156)
	AW with 98Ar/2O_2	82,100 (566)	66,200 (456)	27	120 (163)	90 (122)	80 (108)
	SR with 98Ar/2O_2	78,500 (541)	60,400 (416)	34	160 (217)	140 (190)	130 (176)
	SR with 98Ar/2O_2	79,000 (545)	63,400 (437)	33		115 (156)	

AW - As welded. SR[1] - Stress relieved 1 hour at 1150°F (621°C). SR[2] - Stress relieved 2 hours at 1125°F (607°C).

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LINCOLN ELECTRIC

WELD ENGINEERING

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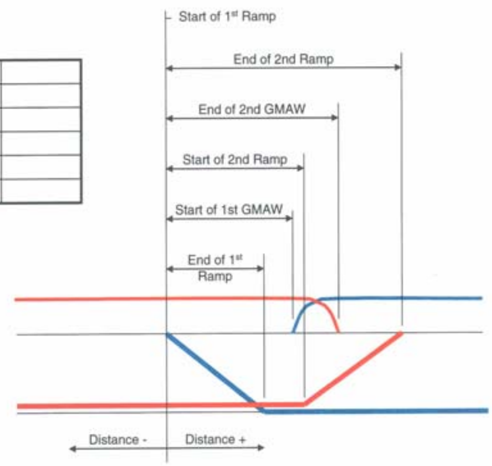
Start of 1st Ramp	
End of 1st Ramp	
Start of 1st GMAW	
Start of 2nd Ramp	
End of 2nd Ramp	
End of 2nd GMAW	



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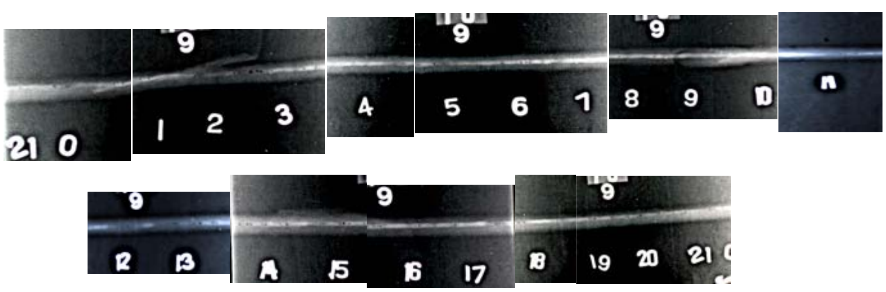
(PQR)

NP-11A1.1



X-RAY Results

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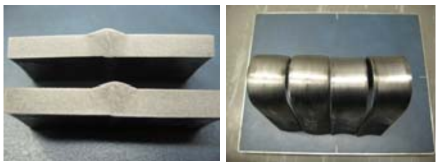
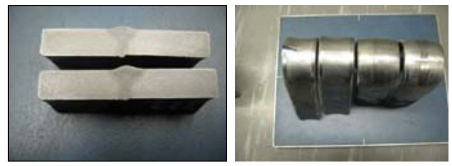
MACRO AND BEND TESTS

This phase of testing consisted of weld evaluation with specified pipes sizes and establishing parameter setting that provided acceptable weldability And satisfied V.T. Acceptance Criteria. (Next two pages)

TEST ID No.	PIPE SIZE	JOINT TYPE	W.F.S
07-214	4 in. dia., Sch 40, 0.237 in. wall	Butt	250 ipm
07-215	6 in. dia., Sch 40, 0.280 in. wall	Butt	250 ipm
07-211	8 in. dia., Sch 40, 0.337 in. wall	Butt	250 ipm
07-212	4 in. dia., Sch 80, 0.337 in. wall	Butt	250 ipm
07-202	8 in. dia., Sch 80, 0.380 in. wall	Butt	400 ipm



Test ID No. 07-214



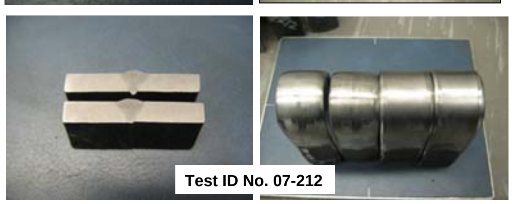
Test ID No. 07-215

WELD ENGINEERING

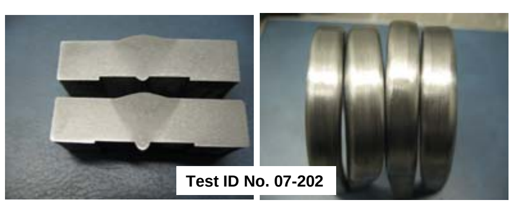
GENERAL DYNAMICS
NASSCO

MACRO AND BEND TESTS

Test ID No. 07-211



Test ID No. 07-212



Test ID No. 07-202

WELD ENGINEERING

GENERAL DYNAMICS

nassco

RADIOGRAPHIC TEST RESULTS

The next set of pipes were X-Rayed and radiographic test results were acceptble. Mechanical Testing will include bends and tensiles to qualify these sizes.

TEST ID No.	PIPE SIZE	JOINT TYPE	W.F.S.
07-213	4 in. dia., Sch. 40, 0.237 in. wall	Butt	250 ipm

Results -- Acceptable
Defects -- 9-12 in. view, 6 Pores = 0.030” dia. @ 10 = 0.004 sq. in.s (Total porosity area allowed is 0.007 sq in. per 3 in. weld length)

07-209 6 in. dia., Sch. 40, 0.280 in. wall Butt 250 ipm

Results -- Acceptable
Defects -- 7-11 in. view, 11 Pores <= 1/64” dia. = disregard
6 Pores = 0.030” dia. = 0.004 sq. in.s (Total porosity area allowed is 0.0112 sq in. per 4 in. weld length)

07-216 8 in. dia., Sch. 40, 0.322 in. wall Butt 250 ipm

Results -- Acceptable

07-218 4 in. dia., Sch. 80, 0.337 in. wall Butt 250 ipm

Results -- Acceptable
Defects -- 0-3 in. view, 11 Pores <= 1/64” dia. = disregard
3-6 in. view, 1 Pores = 0.030” dia.

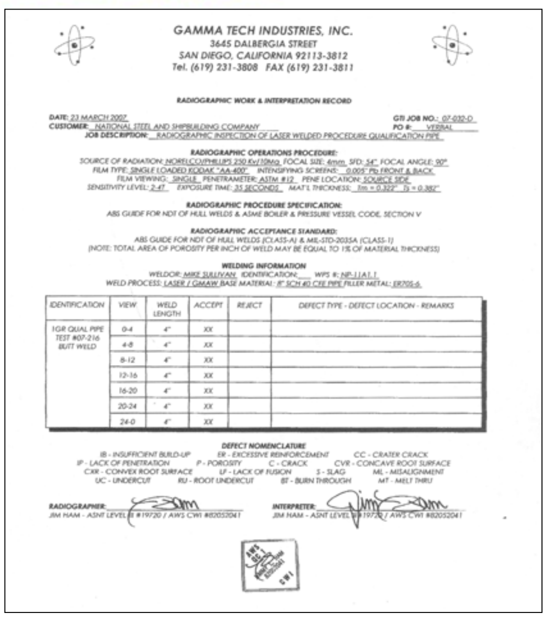
WELD ENGINEERING

GENERAL DYNAMICS

nassco

Test No.

07- 216



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Tel. (619) 231-3808 FAX (619) 231-3811

RADIOGRAPHIC WORK & INTERPRETATION RECORD

DATE: 23 MARCH 2007 GTI JOB NO.: 07-032-D
CUSTOMER: NATIONAL STEEL AND SHIPBUILDING COMPANY PO #: VERBAL
JOB DESCRIPTION: RADIOGRAPHIC INSPECTION OF LASER WELDED PROCEDURE QUALIFICATION PIPE

RADIOGRAPHIC OPERATIONS PROCEDURE:
SOURCE OF RADIATION: NORELCO/PHILLIPS 250 Kv/10Ma FOCAL SIZE: 4mm SFD: 54" FOCAL ANGLE: 90°
FILM TYPE: SINGLE LOADED KODAK "AA-400" INTENSIFYING SCREENS: 0.005" Pb FRONT & BACK
FILM VIEWING: SINGLE PENETRAMETER: ASTM #12 PENE LOCATION: SOURCE SIDE
SENSITIVITY LEVEL: 2-4T EXPOSURE TIME: 35 SECONDS MAT'L THICKNESS: Tm = 0.322" Ts = 0.382"

RADIOGRAPHIC PROCEDURE SPECIFICATION:
ABS GUIDE FOR NDT OF HULL WELDS & ASME BOILER & PRESSURE VESSEL CODE, SECTION V

RADIOGRAPHIC ACCEPTANCE STANDARD:
ABS GUIDE FOR NDT OF HULL WELDS (CLASS-A) & MIL-STD-2035A (CLASS-1)
(NOTE: TOTAL AREA OF POROSITY PER INCH OF WELD MAY BE EQUAL TO 1% OF MATERIAL THICKNESS)

WELDING INFORMATION
WELDOR: MIKE SULLIVAN IDENTIFICATION: ___ WPS #: NP-11A1.1
WELD PROCESS: LASER / GMAW BASE MATERIAL: 8" SCH 40 CFE PIPE FILLER METAL: ER70S-6

IDENTIFICATION	VIEW	WELD LENGTH	ACCEPT	REJECT	DEFECT TYPE - DEFECT LOCATION - REMARKS
1GR QUAL PIPE TEST #07-216 BUTT WELD	0-4	4"	XX		
	4-8	4"	XX		
	8-12	4"	XX		
	12-16	4"	XX		
	16-20	4"	XX		
	20-24	4"	XX		
	24-0	4"	XX		

DEFECT NOMENCLATURE
IB - INSUFFICIENT BUILD-UP ER - EXCESSIVE REINFORCEMENT CC - CRATER CRACK
IP - LACK OF PENETRATION P - POROSITY C - CRACK CVR - CONCAVE ROOT SURFACE
CXR - CONVEX ROOT SURFACE LF - LACK OF FUSION S - SLAG ML - MISALIGNMENT
UC - UNDERCUT RU - ROOT UNDERCUT BT - BURN THROUGH MT - MELT THRU

RADIOGRAPHER: [signature]
JIM HAM - ASNT LEVEL II #19720 / AWS CWI #82052041

INTERPRETER: [signature]
JIM HAM - ASNT LEVEL II #19720 / AWS CWI #82052041

WELD ENGINEERING

GENERAL DYNAMICS

NASSCO

GAMMA TECH INDUSTRIES, INC.
3645 DALBERGIA STREET
SAN DIEGO, CALIFORNIA 92113-3812
Tel. (619) 231-3808 FAX (619) 231-3811

RADIOGRAPHIC WORK & INTERPRETATION RECORD

DATE: 23 MARCH 2007 — GTI JOB NO.: 07-032-C
CUSTOMER: NATIONAL STEEL AND SHIPBUILDING COMPANY — PO #: VERBAL
JOB DESCRIPTION: RADIOGRAPHIC INSPECTION OF LASER WELDED PROCEDURE QUALIFICATION PIPE

RADIOGRAPHIC OPERATIONS PROCEDURE:
SOURCE OF RADIATION: NORELCO/PHILLIPS 250 Kv/10Ma FOCAL SIZE: 4mm SFD: 54" FOCAL ANGLE: 90°
FILM TYPE: SINGLE LOADED KODAK "AA-400" INTENSIFYING SCREENS: 0.005" Pb FRONT & BACK
FILM VIEWING: SINGLE PENETRAMETER: ASTM #12 PENE LOCATION: SOURCE SIDE
SENSITIVITY LEVEL: 2-4T EXPOSURE TIME: 35 SECONDS MAT'L THICKNESS: Tm = 0.280" Ts = 0.340"

RADIOGRAPHIC PROCEDURE SPECIFICATION:
ABS GUIDE FOR NDT OF HULL WELDS & ASME BOILER & PRESSURE VESSEL CODE, SECTION V

RADIOGRAPHIC ACCEPTANCE STANDARD:
ABS GUIDE FOR NDT OF HULL WELDS (CLASS-A) & MIL-STD-2035A (CLASS-1)
(NOTE: TOTAL AREA OF POROSITY PER INCH OF WELD MAY BE EQUAL TO 1% OF MATERIAL THICKNESS)

WELDING INFORMATION
WELDOR: MIKE SULLIVAN IDENTIFICATION: ___ WPS #: NP-11A1.1
WELD PROCESS: LASER / GMAW BASE MATERIAL: 6" SCH 40 CFE PIPE FILLER METAL: ER70S-6

IDENTIFICATION	VIEW	WELD LENGTH	ACCEPT	REJECT	DEFECT TYPE - DEFECT LOCATION - REMARKS
1GR QUAL PIPE TEST #07-209 BUTT WELD	0-4	4"	XX		ACCEPTABLE POROSITY
	3-8	4"	XX		ACCEPTABLE POROSITY
	7-11	4"	XX		11 PORES ≤ 1/64" = DISREGARD 6 PORES = .030" = .004 Sq In **(TOTAL POROSITY AREA ALLOWED IS .0112 Sq In PER 4" LENGTH)**
	10-14	4"	XX		ACCEPTABLE POROSITY
	13-18	4"	XX		ACCEPTABLE POROSITY
	17-0	4"	XX		ACCEPTABLE POROSITY

DEFECT NOMENCLATURE
IB - INSUFFICIENT BUILD-UP ER - EXCESSIVE REINFORCEMENT CC - CRATER CRACK
IP - LACK OF PENETRATION P - POROSITY C - CRACK CVR - CONCAVE ROOT SURFACE
CXR - CONVEX ROOT SURFACE LF - LACK OF FUSION S - SLAG ML - MISALIGNMENT
UC - UNDERCUT RU - ROOT UNDERCUT BT - BURN THROUGH MT - MELT THRU

RADIOGRAPHER: Jim Ham
JIM HAM - ASNT LEVEL III #19720 / AWS CWI #82052041

INTERPRETER: Jim Ham
JIM HAM - ASNT LEVEL III #19720 / AWS CWI #82052041

AWS QC-1 CWI

Test No. 07- 209

WELD ENGINEERING

GENERAL DYNAMICS

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RADIOGRAPHIC WORK & INTERPRETATION RECORD

DATE: 23 MARCH 2007 — GTI JOB NO.: 07-032-B
CUSTOMER: NATIONAL STEEL AND SHIPBUILDING COMPANY — PO #: VERBAL
JOB DESCRIPTION: RADIOGRAPHIC INSPECTION OF LASER WELDED PROCEDURE QUALIFICATION PIPE

RADIOGRAPHIC OPERATIONS PROCEDURE:
SOURCE OF RADIATION: NORELCO/PHILLIPS 250 Kv/10Ma FOCAL SIZE: 4mm SFD: 54" FOCAL ANGLE: 90°
FILM TYPE: SINGLE LOADED KODAK "AA-400" INTENSIFYING SCREENS: 0.005" Pb FRONT & BACK
FILM VIEWING: SINGLE PENETRAMETER: ASTM #12 PENE LOCATION: SOURCE SIDE
SENSITIVITY LEVEL: 2-4T EXPOSURE TIME: 35 SECONDS MAT'L THICKNESS: Tm = 0.337" Ts = 0.397"

RADIOGRAPHIC PROCEDURE SPECIFICATION:
ABS GUIDE FOR NDT OF HULL WELDS & ASME BOILER & PRESSURE VESSEL CODE, SECTION V

RADIOGRAPHIC ACCEPTANCE STANDARD:
ABS GUIDE FOR NDT OF HULL WELDS (CLASS-A) & MIL-STD-2035A (CLASS-1)
(NOTE: TOTAL AREA OF POROSITY PER INCH OF WELD MAY BE EQUAL TO 1% OF MATERIAL THICKNESS)

WELDING INFORMATION
WELDOR: MIKE SULLIVAN IDENTIFICATION: ___ WPS #: NP-11A1.1
WELD PROCESS: LASER / GMAW BASE MATERIAL: 4" SCH 80 CFE PIPE FILLER METAL: ER70S-6

IDENTIFICATION	VIEW	WELD LENGTH	ACCEPT	REJECT	DEFECT TYPE - DEFECT LOCATION - REMARKS
1GR QUAL PIPE TEST #07-218 BUTT WELD	0-3	3"	XX		11 PORES ≤ 1/64" = DISREGARD
	3-6	3"	XX		.030" PORE @ 4.5
	6-9	3"	XX		
	9-12	3"	XX		
	12-0	3"	XX		

DEFECT NOMENCLATURE
IB - INSUFFICIENT BUILD-UP ER - EXCESSIVE REINFORCEMENT CC - CRATER CRACK
IP - LACK OF PENETRATION P - POROSITY C - CRACK CVR - CONCAVE ROOT SURFACE
CXR - CONVEX ROOT SURFACE LF - LACK OF FUSION S - SLAG ML - MISALIGNMENT
UC - UNDERCUT RU - ROOT UNDERCUT BT - BURN THROUGH MT - MELT THRU

RADIOGRAPHER: Jim Ham
JIM HAM - ASNT LEVEL III #19720 / AWS CWI #82052041

INTERPRETER: Jim Ham
JIM HAM - ASNT LEVEL III #19720 / AWS CWI #82052041

AWS QC-1 CWI

Test No. 07- 218

WELD ENGINEERING

GENERAL DYNAMICS
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RADIOGRAPHIC WORK & INTERPRETATION RECORD

DATE: 23 MARCH 2007 **GTI JOB NO.:** 07-032-A
CUSTOMER: NATIONAL STEEL AND SHIPBUILDING COMPANY **PO #:** VERBAL
JOB DESCRIPTION: RADIOGRAPHIC INSPECTION OF LASER WELDED PROCEDURE QUALIFICATION PIPE

RADIOGRAPHIC OPERATIONS PROCEDURE:
SOURCE OF RADIATION: NORELCO/PHILLIPS 250 Kv/10Ma FOCAL SIZE: 4mm SFD: 54" FOCAL ANGLE: 90°
FILM TYPE: SINGLE LOADED KODAK "AA-400" INTENSIFYING SCREENS: 0.005" Pb FRONT & BACK
FILM VIEWING: SINGLE PENETRAMETER: ASTM #10 PENE LOCATION: SOURCE SIDE
SENSITIVITY LEVEL: 2-4T EXPOSURE TIME: 25 SECONDS MAT'L THICKNESS: Tm = 0.240" Ts = 0.300"

RADIOGRAPHIC PROCEDURE SPECIFICATION:
ABS GUIDE FOR NDT OF HULL WELDS & ASME BOILER & PRESSURE VESSEL CODE, SECTION V

RADIOGRAPHIC ACCEPTANCE STANDARD:
ABS GUIDE FOR NDT OF HULL WELDS (CLASS-A) & MIL-STD-2035A (CLASS-1)
(NOTE: TOTAL AREA OF POROSITY PER INCH OF WELD MAY BE EQUAL TO 1% OF MATERIAL THICKNESS)

WELDING INFORMATION
WELDOR: MIKE SULLIVAN IDENTIFICATION: ___ WPS #: NP-11A1.1
WELD PROCESS: LASER / GMAW BASE MATERIAL: 4" SCH 40 CFE PIPE FILLER METAL: ER70S-6

IDENTIFICATION	VIEW	WELD LENGTH	ACCEPT	REJECT	DEFECT TYPE - DEFECT LOCATION - REMARKS
1GR QUAL PIPE TEST #07-213 BUTT WELD	0-3	3"	XX		
	3-6	3"	XX		
	6-9	3"	XX		
	9-12	3"	XX		6 PORES = .030" DIA @ 10 = .004 Sq In **(TOTAL POROSITY AREA ALLOWED IS 0.007 Sq In PER 3" WELD LENGTH)**
	12-0	3"	XX		

DEFECT NOMENCLATURE
IB - INSUFFICIENT BUILD-UP ER - EXCESSIVE REINFORCEMENT CC - CRATER CRACK
IP - LACK OF PENETRATION P - POROSITY C - CRACK CVR - CONCAVE ROOT SURFACE
CXR - CONVEX ROOT SURFACE LF - LACK OF FUSION S - SLAG ML - MISALIGNMENT
UC - UNDERCUT RU - ROOT UNDERCUT BT - BURN THROUGH MT - MELT THRU

RADIOGRAPHER: Jim Ham
JIM HAM - ASNT LEVEL III #19720 / AWS CWI #82052041

INTERPRETER: Jim Ham
JIM HAM - ASNT LEVEL III #19720 / AWS CWI #82052041

AWS QC 1 JIMMY L. HAM 82052041 CWI

Test No.
07- 213

WELD ENGINEERING

Hybrid Laser Pipe Welding System presentation given by General Dynamics NASSCO 20 August 2007 contained NASSCO proprietary information. For more information please contact, CNST at (843) 760-3374.

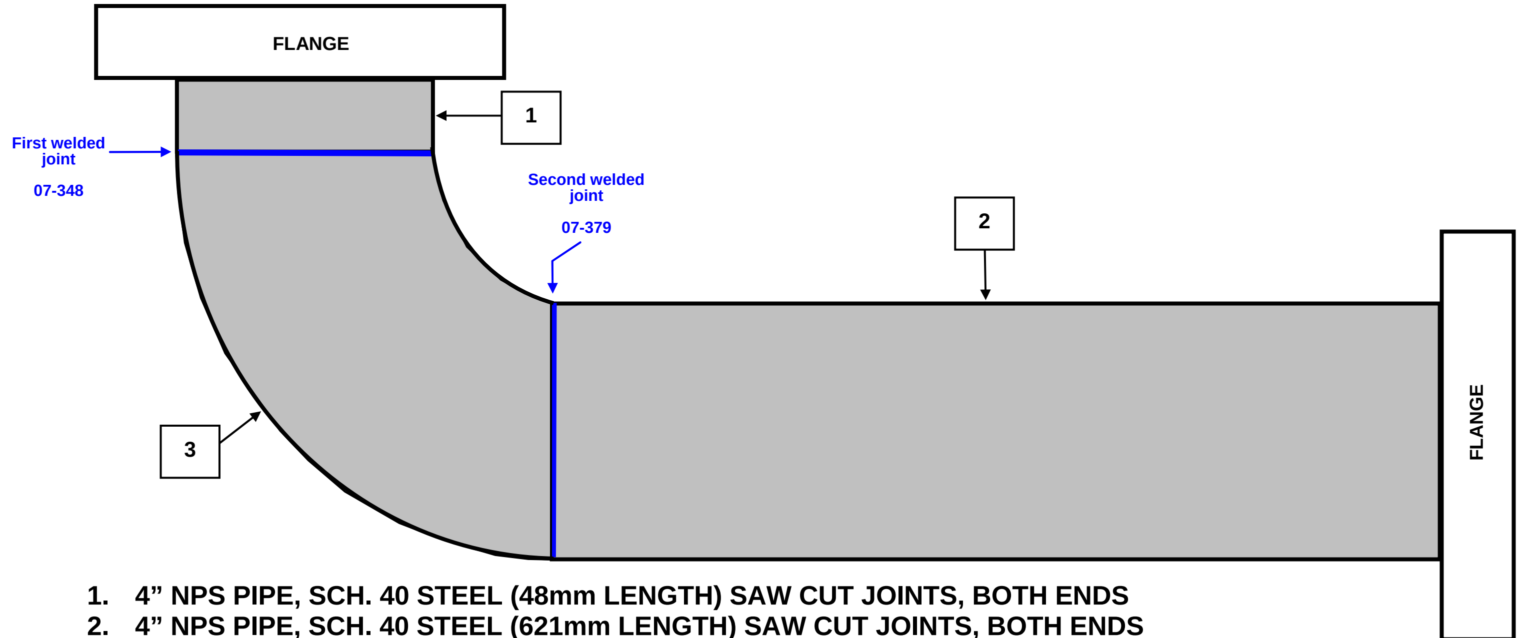
GENERAL DYNAMICS
nassco

WELDING ENGINEERING

04/23/07

FIRST PRODUCTION PIPE WELDED BY HYBRID LASER

04/11/07 – 4/12/07



1. 4" NPS PIPE, SCH. 40 STEEL (48mm LENGTH) SAW CUT JOINTS, BOTH ENDS
2. 4" NPS PIPE, SCH. 40 STEEL (621mm LENGTH) SAW CUT JOINTS, BOTH ENDS
3. 4" NPS ELBOW 90^0, BUTT. STEEL, MACHINED OFF BEVELS

HOURS USED

To machine both ends of the Elbow by Machine Shop = 30 min
To fit the (2) pipes by Pipe fitter = 30 min
Set-up and Weld both joints = 15 min
Weld repair on ID, first welded joint = 15 min

1 HOUR 30 MIN. TOTAL

GENERAL NOTE:
FLANGES WHERE INSTALLED AFTER LASER WELDING WAS COMPLETED

H:/ Hybrid / Production Pipe Spool hours.doc

GENERAL DYNAMICS
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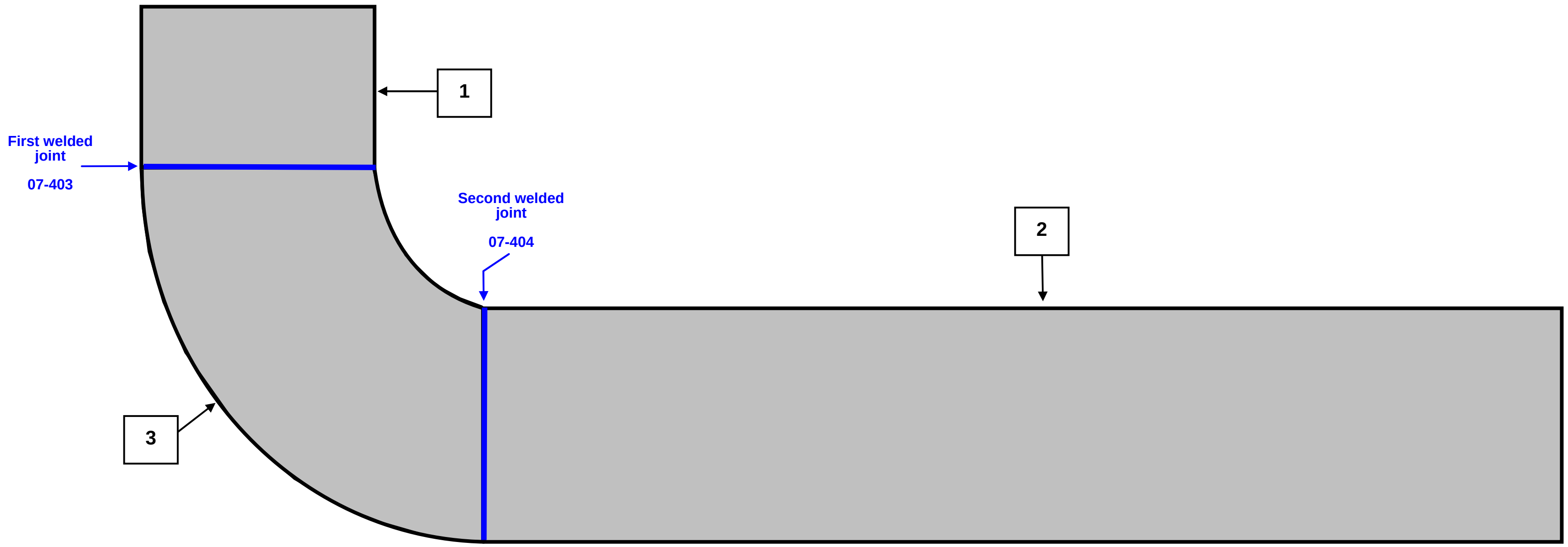
WELDING ENGINEERING

04/23/07

SECOND PRODUCTION PIPE WELDED BY HYBRID LASER

04/18/07



1. 4" NPS PIPE, SCH. 80 STEEL (140mm LENGTH) SAW CUT JOINTS, BOTH ENDS
2. 4" NPS PIPE, SCH. 80 STEEL (1436mm LENGTH) SAW CUT JOINTS, BOTH ENDS
3. 4" NPS ELBOW 90^0, BUTT. STEEL, MACHINED OFF BEVELS

HOURS USED

To machine both ends of the Elbow by Machine Shop = 1 Hr
To fit the (2) pipes by Pipe fitter = 30 min
Set-up and Weld both joints = 20 min

1 HOUR 50 MIN TOTAL

GENERAL DYNAMICS
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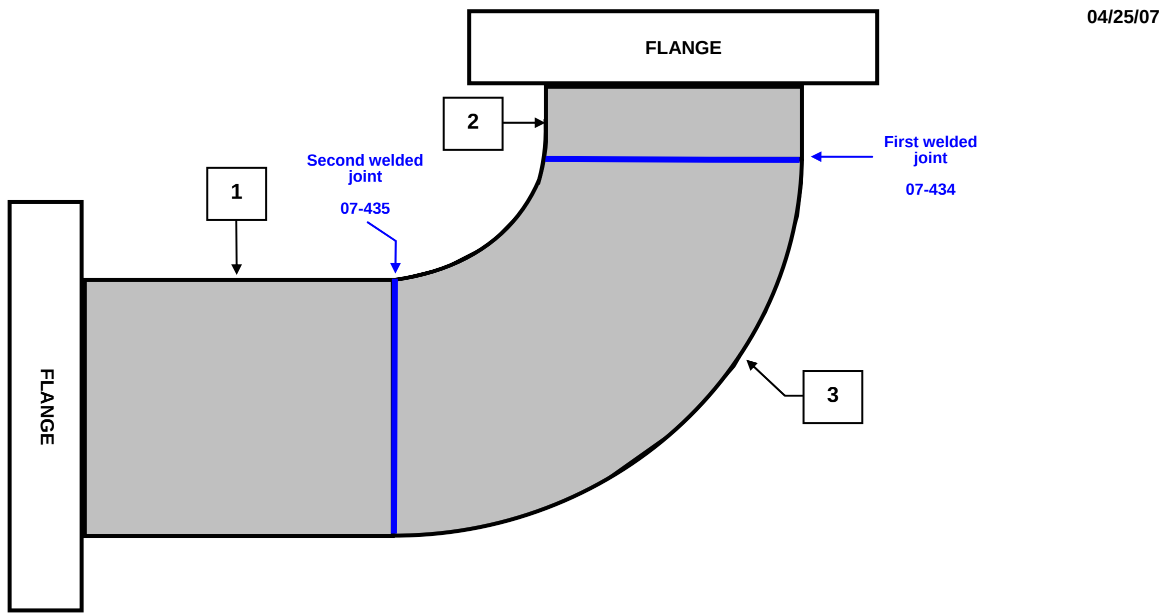
WELDING ENGINEERING

04/23/07

THIRD PRODUCTION PIPE WELDED BY HYBRID LASER



1. 8" NPS PIPE, SCH. 40 STEEL (133mm LENGTH) SAW CUT JOINTS, BOTH ENDS
2. 8" NPS PIPE, SCH. 40 STEEL (87mm LENGTH) SAW CUT JOINTS, BOTH ENDS
3. 8" NPS ELBOW 90^0, BUTT. STEEL, MACHINED OFF BEVELS

HOURS USED

To machine both ends of the Elbow by Machine Shop = 1.30 hrs
To grind and fit up (2) pipes by Pipe fitter = 1 hr
Set-up and Weld both joints = 30 min

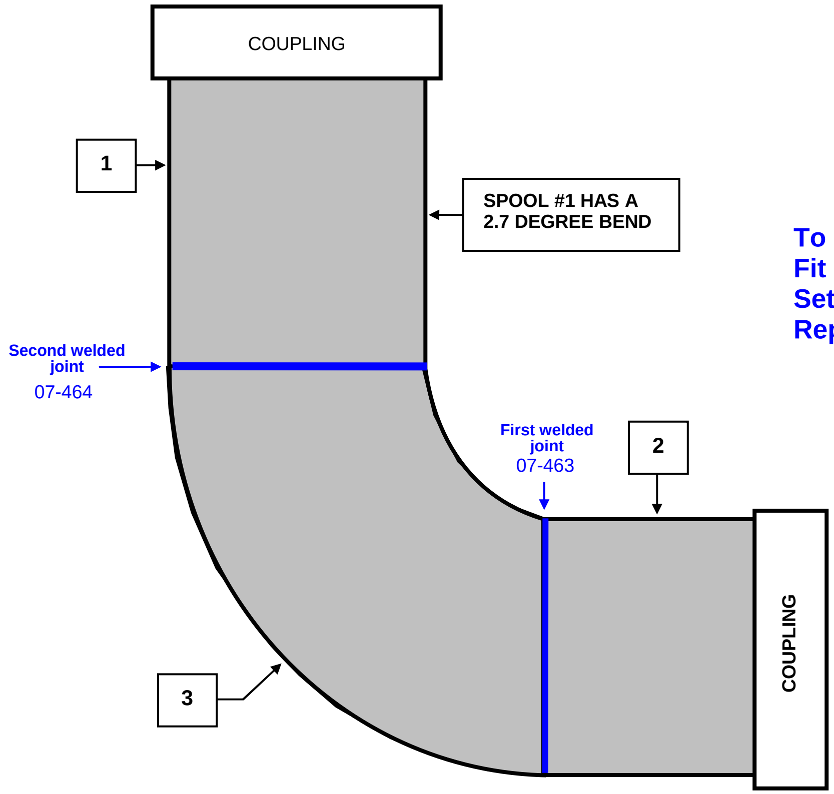
3 HOURS TOTAL

GENERAL NOTE:

FLANGES WHERE INSTALLED AFTER LASER WELDING WAS COMPLETED

FOURTH PRODUCTION PIPE WELDED BY HYBRID LASER

05/10/07



HOURS USED

To set-up & machine Elbow & Pipes = 2 hrs
Fit up (2) pipes by Pipe fitter = 1 hr
Set-up and Weld both joints = 30 min
Repaired ID weld on first joint, ID under = 45 min

4.2 HOURS TOTAL

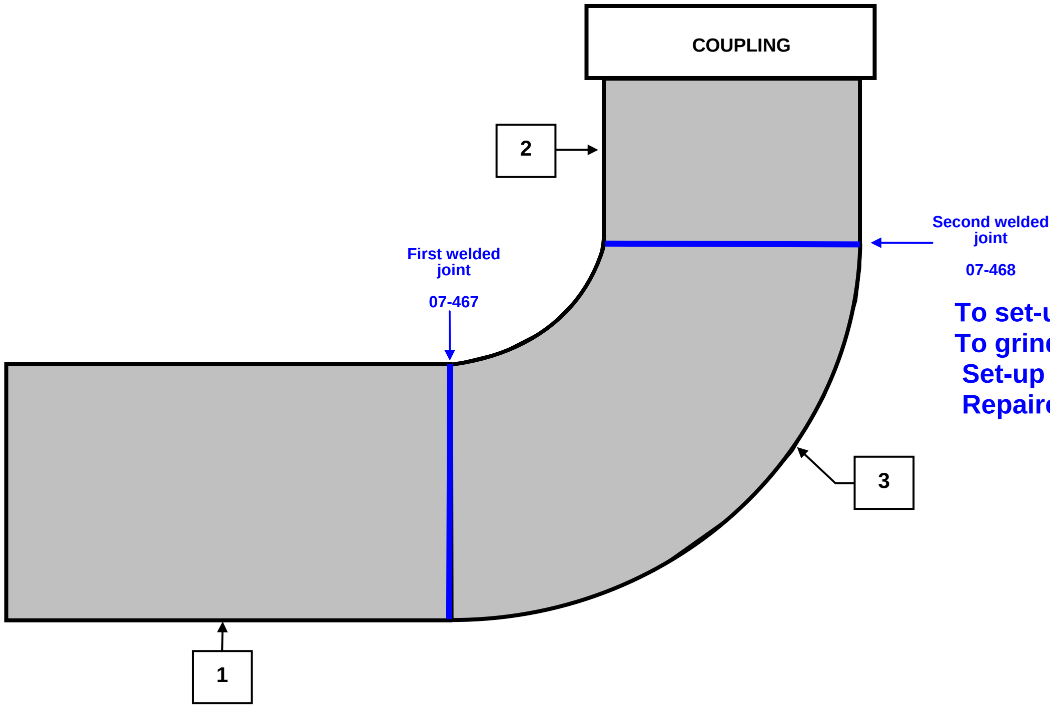
1. 10” NPS PIPE, SCH. 40 STEEL (442mm LENGTH) SAW CUT JOINTS, BOTH ENDS
2. 10” NPS PIPE, SCH. 40 STEEL (350mm LENGTH) SAW CUT JOINTS, BOTH ENDS
3. 10” NPS ELBOW 90^0, BUTT. STEEL, MACHINED OFF BEVELS

GENERAL NOTE:

COUPLINGS WHERE INSTALLED AFTER LASER WELDING WAS COMPLETED

FIFTH PRODUCTION PIPE WELDED BY HYBRID LASER

05/18/07



HOURS USED

To set-up & machine both ends of Elbow = 1.5 hrs
To grind and fit up (2) pipes by Pipe fitter = 1.0 Hr
Set-up and Weld both joints = 0.5 Hr
Repaired ID weld on first joint, ID under = 1.2 Hrs

4.2 HOURS TOTAL for (2 joints)

GENERAL NOTE:

COUPLING WAS INSTALLED AFTER LASER WELDING WAS COMPLETED

1. **8” NPS PIPE, SCH. 80 STEEL (252mm LENGTH) SAW CUT JOINTS, THEN MACHINED**
2. **8” NPS PIPE, SCH. 80 STEEL (234mm LENGTH) SAW CUT JOINTS, THEN MACHINED**
3. **8” NPS ELBOW 90^0, BUTT. STEEL, MACHINED OFF BEVELS**

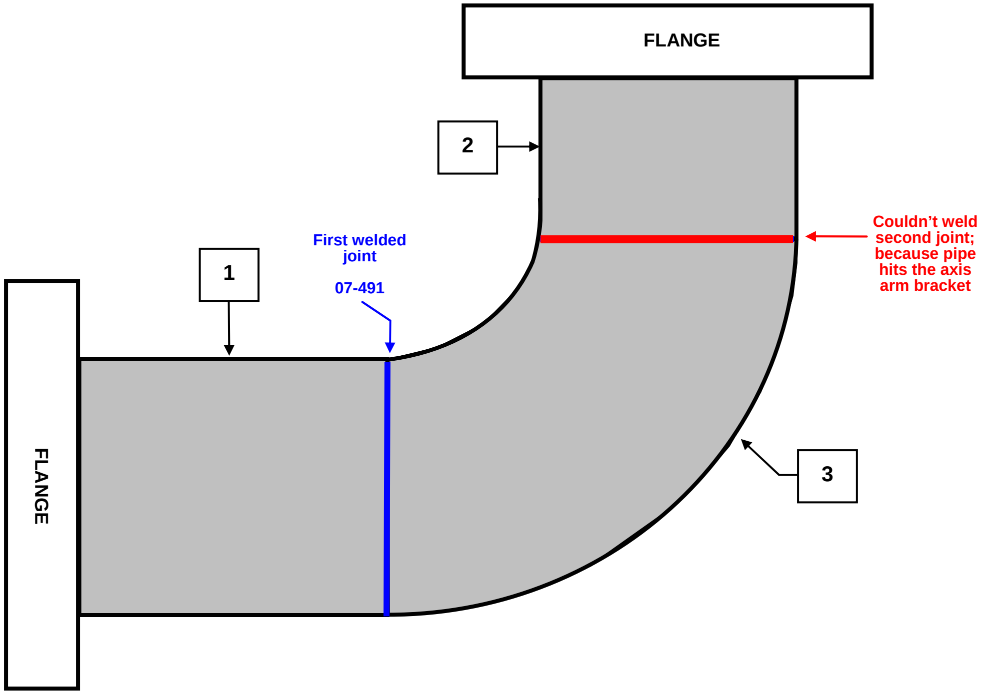
GENERAL DYNAMICS
nassco

WELDING ENGINEERING

04/23/07

SIXTH PRODUCTION PIPE WELDED BY HYBRID LASER

05/23/07



HOURS USED

To set-up & machine both ends of Elbow = 45 min
To grind and fit up (1) pipe by Pipe fitter = 45 min.
Set-up and Weld (1) joint = 30 min
Repaired ID weld on first joint, ID 2"concave = 10 min

TOTAL 2.2 HOURS for (1 joint)

1. 8" NPS PIPE, SCH. 40 STEEL (261mm LENGTH) SAW CUT JOINTS, THEN MACHINED
2. 8" NPS PIPE, SCH. 40 STEEL (191mm LENGTH) SAW CUT JOINTS, THEN MACHINED
3. 8" NPS ELBOW 90^0, SHORT R, BUTT. STEEL, MACHINED OFF BEVELS

GENERAL NOTE:

FLANGES WHERE INSTALLED AFTER LASER WELDING WAS COMPLETED

GENERAL DYNAMICS
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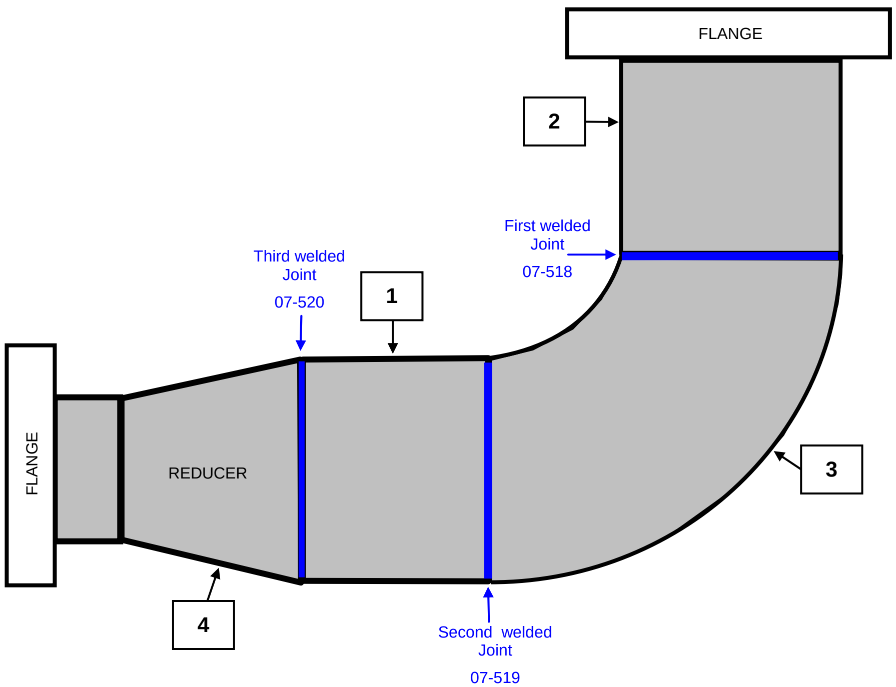
WELDING ENGINEERING

04/23/07

SEVENTH PRODUCTION PIPE WELDED BY HYBRID LASER

06/05



HOURS USED

To set-up & machine both pipe ends, Elbow and one side of the reducer------------------------ = 1.5 Hr
To grind and fit up (3) pipe joints by Pipe fitter = 1.2 Hr
Set-up and Weld (3) joints -------------------------- = 45 min
Repaired (2) tie-ends on OD. ---------------------- = 20 min

TOTAL 3.7 HOURS FOR (3 joints)

1. 6" NPS PIPE, SCH. 40 STEEL (132mm LENGTH) SAW CUT JOINTS, THEN MACHINED
2. 6" NPS PIPE, SCH. 40 STEEL (147mm LENGTH) SAW CUT JOINTS, THEN MACHINED
3. 6" NPS ELBOW 90^0, LONG R, BUTT. STEEL, MACHINED OFF BEVELS
4. 6" X 5" NPS REDUCER, CONCENTRIC, STEEL. MACHINED ON THE 6" SIDE ONLY

GENERAL NOTE:

FLANGES WHERE INSTALLED AFTER LASER WELDING WAS COMPLETED

GENERAL DYNAMICS
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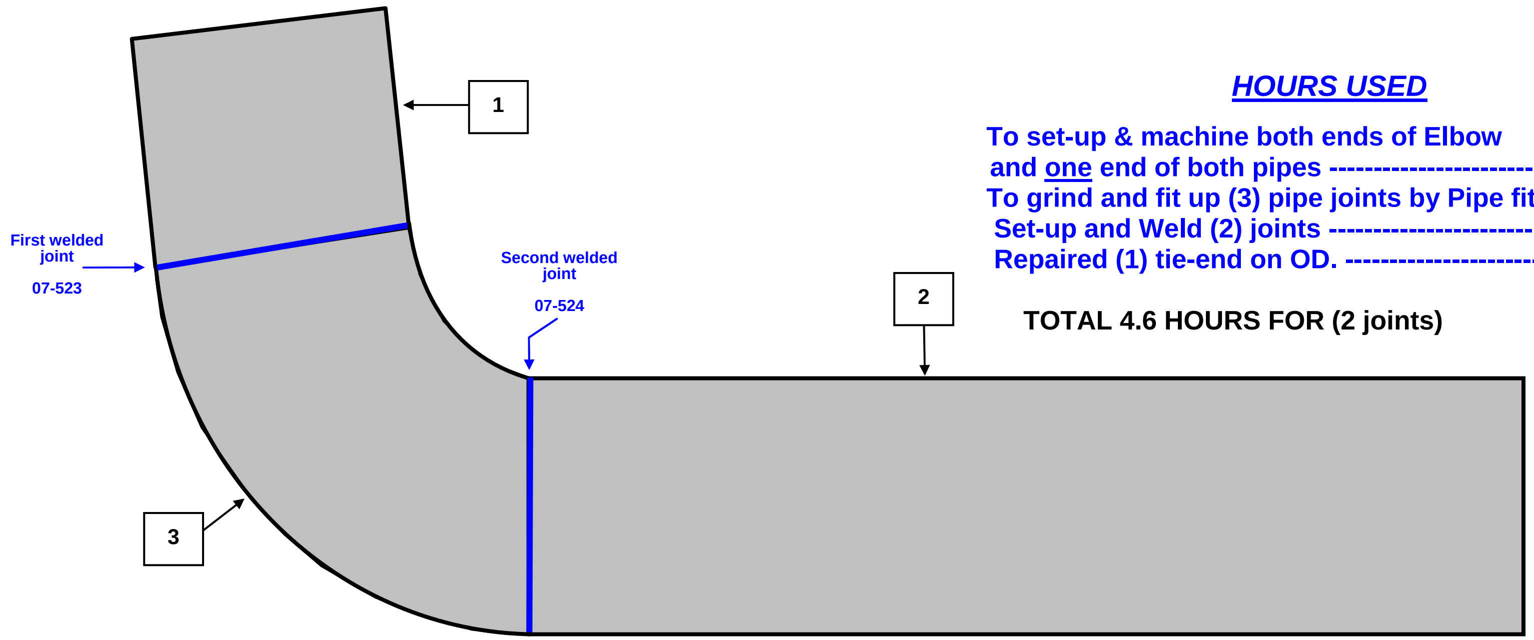
WELDING ENGINEERING

04/23/07

EIGHTH PRODUCTION PIPE WELDED BY HYBRID LASER

06/06



HOURS USED

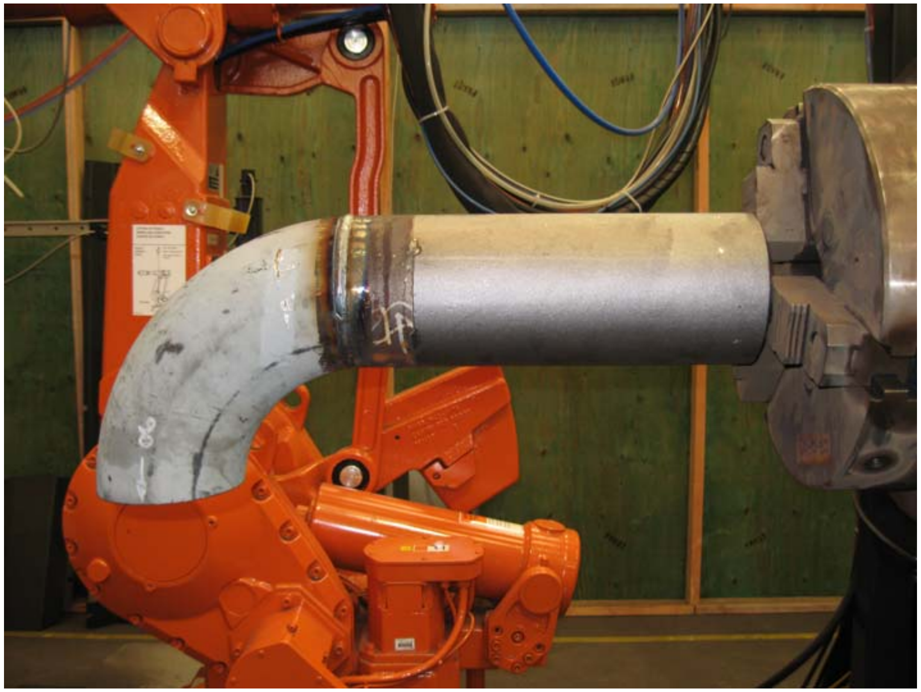
To set-up & machine both ends of Elbow and one end of both pipes -------------------------- = 3.4 Hr
To grind and fit up (3) pipe joints by Pipe fitter = .5 Hr
Set-up and Weld (2) joints -------------------------- = .5 Hr
Repaired (1) tie-end on OD. ------------------------ = .2 Hr

TOTAL 4.6 HOURS FOR (2 joints)

1. 6" NPS PIPE, XS STEEL (358mm LENGTH) SAW CUT JOINTS, THEN ONE SIDE MACHINED W/ .350 LAND.
2. 6" NPS PIPE, XS STEEL (1354mm LENGTH) SAW CUT JOINTS, THEN ONE SIDE MACHINED W/ .350 LAND.
3. 6" NPS ELBOW 90^0, LONG R, BUTT. STEEL, MACHINED OFF BEVELS AND W/ .350 LAND & ONE SIDE (MACHINE) CUT 87.4 DEG.

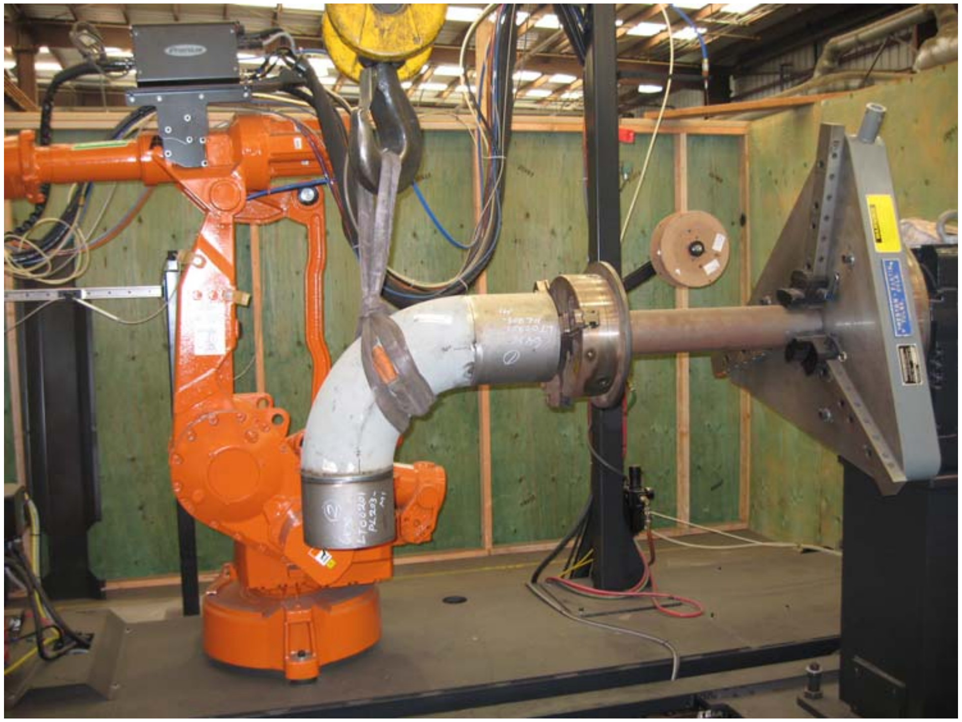
GENERAL NOTE:

FLANGES WHERE INSTALLED AFTER LASER WELDING WAS COMPLETED



First Production Pipe

Second Production Pipe



Third Production Pipe

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WELDING ENGINEERING

04/23/07

Fourth Production Pipe

Fifth Production Pipe

GENERAL DYNAMICS
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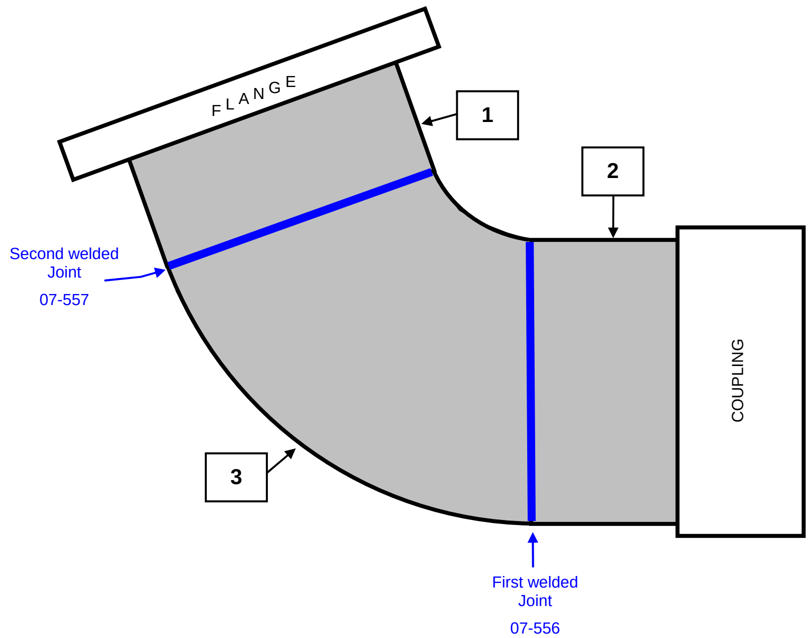
04/23/07

Sixth Production Pipe

Seventh Production Pipe

Eighth Production Pipe

NINTH PRODUCTION PIPE WELDED BY HYBRID LASER



HOURS USED

To set-up & machine both ends of Elbow
and one end of both pipes -------------------------- = 2.0 Hrs
To grind and fit up (2) pipe joints by Pipe fitter = 1.0 Hr
Set-up and Weld (2) joints -------------------------- = 0.5 Hr
Repairs (None) --- = 0 Hrs

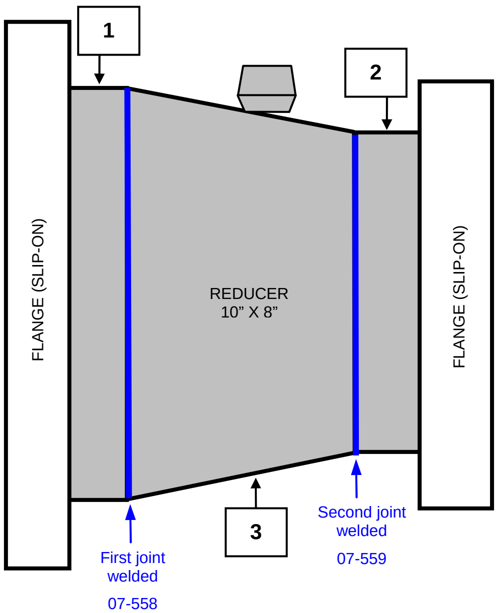
3.5 HOURS TOTAL for (2 joints)

1. 12” NPS PIPE, SCH. 40 STEEL (321mm LENGTH) SAW CUT JOINTS, THEN MACHINED
2. 12” NPS PIPE, SCH. 40 STEEL (369mm LENGTH) SAW CUT JOINTS, THEN MACHINED
3. 12” NPS ELBOW. 45^0, STEEL, MACHINED OFF BEVELS

GENERAL NOTE:

FLANGE AND COUPLING WHERE INSTALLED AFTER LASER WELDING WAS COMPLETED

TENTH PRODUCTION PIPE WELDED BY HYBRID LASER



HOURS USED

To set-up & machine both ends of Reducer
and one end of both pipes -------------------------- = 1.2 Hrs
To grind and fit up (3) pipe joints by Pipe fitter = 0.5 Hr
Set-up and Weld (2) joints -------------------------- = 0.5 Hr
Repaired ID on (2nd joint) half w/concavity ----- = 0.5 Hr

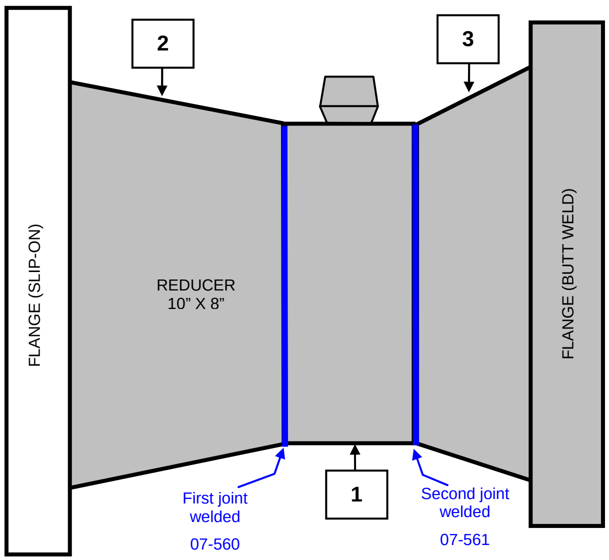
TOTAL 2.7 HOURS TOTAL for (2 joints)

1. 10" NPS PIPE, SCH. 40 STEEL (55mm LENGTH) SAW CUT JOINTS, THEN MACHINED ONE END 90^0
2. 8" NPS PIPE, SCH. 40 STEEL (50mm LENGTH) SAW CUT JOINTS, THEN MACHINED ONE END 90^0
3. 10 x 8 IN. NPS REDUCER, SCH. 40, STEEL, MACHINED OFF BEVELS TO 90^0

GENERAL NOTE:

SLIP ON FLANGES AND SOCKOLET WHERE INSTALLED AFTER LASER WELDING WAS COMPLETED

ELEVENTH PRODUCTION PIPE WELDED BY HYBRID LASER



HOURS USED

To set-up & machine one end of Reducer and the Butt Weld Flange, also both ends of pipe ----- = 2.0 Hrs
To grind and fit up (3) pipe joints by Pipe fitter --- = 0.5 Hr
Set-up and Weld (2) joints ------------------------------- = 0.5 Hr
Repairs (None) --- = 0.0 Hr

3 HOURS TOTAL for (2 joints)

1. 8” NPS PIPE, SCH. 40 STEEL (67mm LENGTH) SAW CUT JOINTS, THEN MACHINED 90^0
2. 10 x 8 NPS REDUCER, STEEL, MACHINED OFF BEVEL TO 90^0
3. 8” NPS FLANGE. BUTT WELD, FLAT FACE, MACHINED OFF BEVEL TO 90^0

GENERAL NOTE:

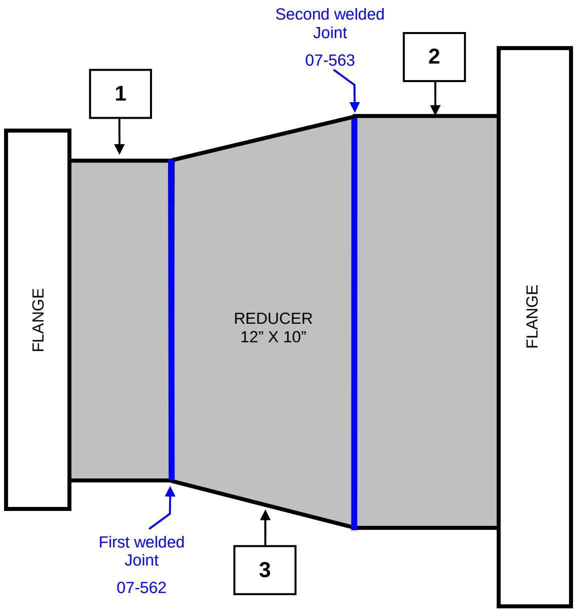
SLIP ON FLANGE AND SOCKOLET WHERE INSTALLED AFTER LASER WELDING WAS COMPLETED

GENERAL DYNAMICS
NASSCO

WELDING ENGINEERING

04/23/07

TWELFTH PRODUCTION PIPE WELDED BY HYBRID LASER



HOURS USED

Set-up to machine both ends of Reducer & pipes --------------- = 4.0 Hrs
To fit up & grind (2) pipe joints by Pipe fitter --------------------- = 0.5 Hr
Set-up and Weld (2) joints -- = 0.5 Hr
Repaired 2nd joint, root (4”of No Penn) & Cover undercut all = 1.0 Hr

6 HOURS TOTAL for (2 joints)

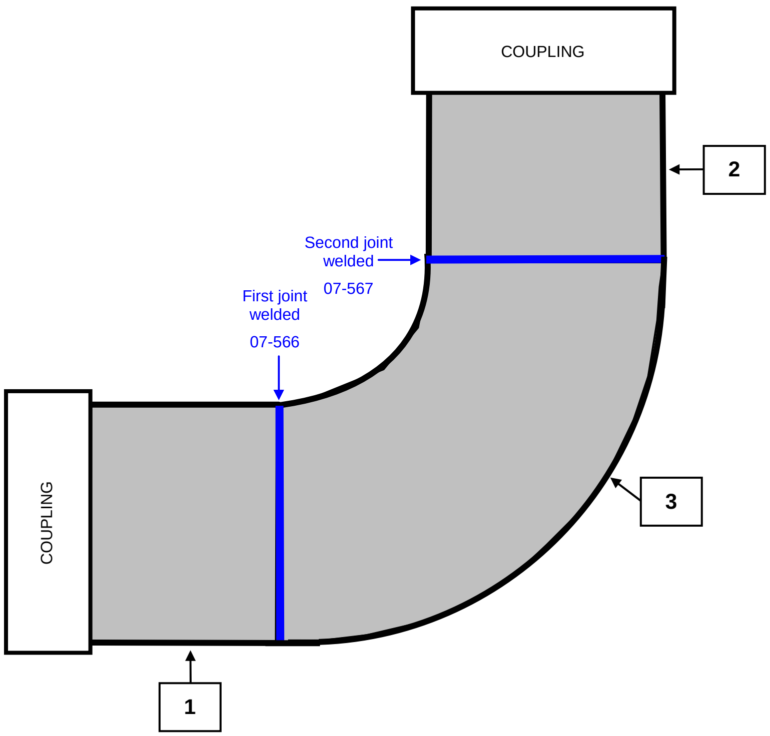
1. 10” NPS PIPE, SCH. XS 80 STEEL (150mm LENGTH) SAW CUT JOINTS, THEN MACHINED ONE END 90^0
2. 12” NPS PIPE, SCH. XS 80 STEEL (143mm LENGTH) SAW CUT JOINTS, THEN MACHINED ONE END 90^0
3. 12 x 10 NPS REDUCER, STEEL, MACHINED OFF BEVELS AND ROUNDED ID.

GENERAL NOTE:
FLANGES WHERE INSTALLED AFTER LASER WELDING WAS COMPLETED

H:/ Hybrid / Production Pipe Spool hours.doc

13TH PRODUCTION PIPE WELDED BY HYBRID LASER

07/02/07



HOURS USED

Set-up to machine both ends of Elbow & pipes -- = 2 Hrs
To fit up & grind (2) pipe joints by Pipe fitter ------ = 1 Hr
Set-up and Weld (2) joints -------------------------------- = .5 Hr
Repaired root on both joints concavity 12" total - = .7 Hr

4.2 HOURS TOTAL for (2 joints)

1. 10" NPS PIPE, SCH. 40 STEEL (287mm LENGTH) SAW CUT JOINTS, THEN MACHINED ONE END 90^0
2. 10" NPS PIPE, SCH. 40 STEEL (260mm LENGTH) SAW CUT JOINTS, THEN MACHINED ONE END 90^0
3. 10" NPS ELBOW LONG R, 90^0, STEEL, MACHINED OFF BEVEL TO 90^0

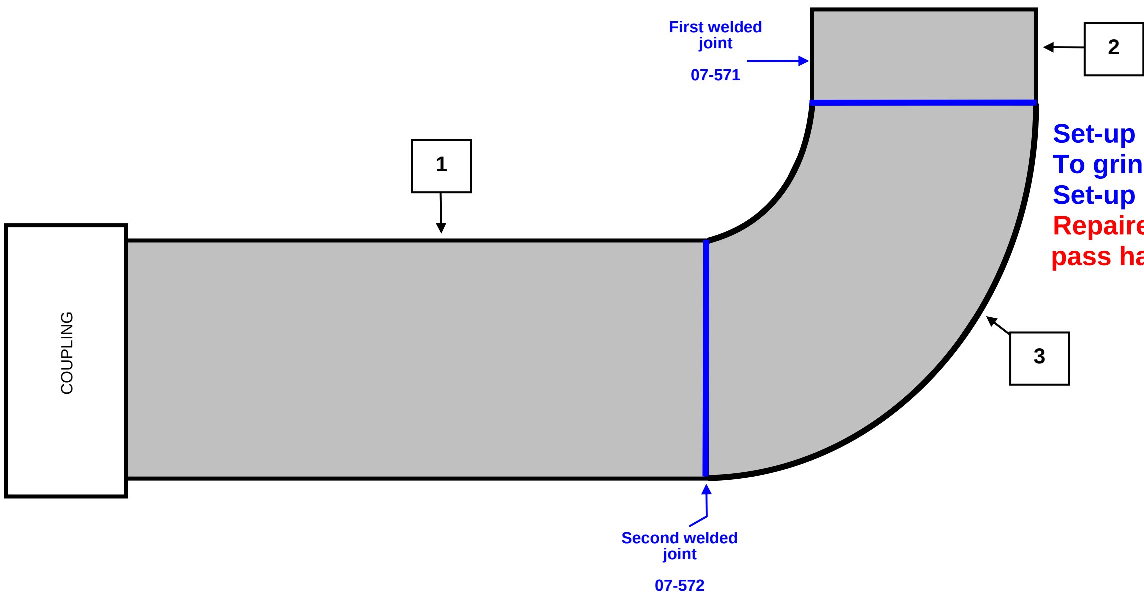
GENERAL NOTE:
COUPLING WHERE INSTALLED AFTER LASER WELDING WAS COMPLETED

GENERAL DYNAMICS
NASSCO

WELDING ENGINEERING

04/23/07

14TH PRODUCTION PIPE WELDED BY HYBRID LASER



HOURS USED

Set-up & machine both ends of Elbow & pipes = 1 Hr
To grind and fit up (2) pipe joints by Pipe fitter = 1 Hr
Set-up and Weld (2) joints --------------------------- = .5 Hr
Repaired 1st joint, Root Convex, 2 spots & Cover pass had under cut, all ------------------------------- = 1 Hr

3.5 HOURS TOTAL for (2 joints)

1. 8" NPS PIPE, SCH. 40 STEEL (731mm LENGTH) SAW CUT JOINTS, THEN MACHINED ONE END TO 90^0
2. 8" NPS PIPE, SCH. 40 STEEL (162mm LENGTH) SAW CUT JOINTS THEN MACHINED ONE END TO 90^0
3. 8" NPS SR ELBOW, 90^0, STEEL, MACHINED OFF BEVELS TO 90^0

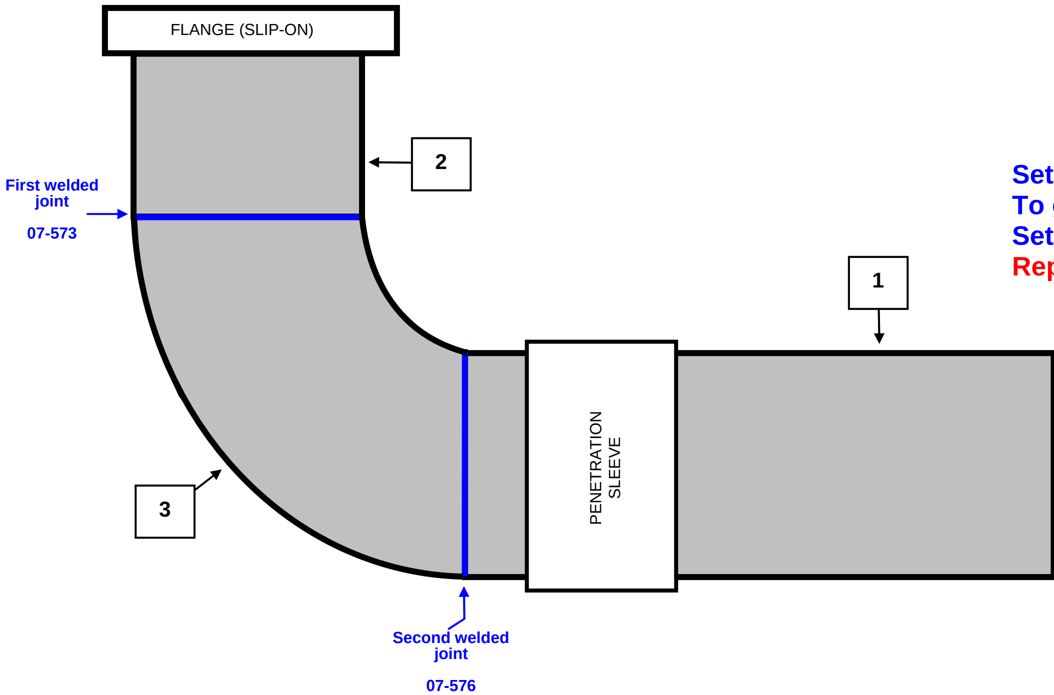
GENERAL NOTE:
COUPLING WAS INSTALLED AFTER LASER WELDING WAS COMPLETED

GENERAL DYNAMICS
nassco

WELDING ENGINEERING

04/23/07

15TH PRODUCTION PIPE WELDED BY HYBRID LASER



HOURS USED

Set-up to machine both ends of Elbow and pipes = 1.5 Hr
To grind and fit up (2) pipe joints by Pipe fitter--- = 1.0 Hr
Set-up and Weld (2) joints ------------------------------ = 0.5 Hr
Repairs (None) --- = 0.0 Hr

3 HOURS TOTAL for (2 joints)

1. 6” IPS PIPE, SCH 80 STEEL (1143mm LENGTH) SAW CUT JOINTS, THEN ONE SIDE MACHINED W/ .350 LAND & 35^0 BEVEL.
2. 6” IPS PIPE, SCH 80 STEEL (130mm LENGTH) SAW CUT JOINTS, THEN ONE SIDE MACHINED W/ .350 LAND & 35^0 BEVEL.
3. 6” NPS ELBOW 90^0, LONG R. STEEL, MACHINED OFF BEVELS AND W/ .350 LAND & 35^0 BEVEL.

GENERAL NOTE:

SLIP ON FLANGE AND PENETRATION SLEEVE WHERE INSTALLED AFTER LASER WELDING WAS COMPLETED

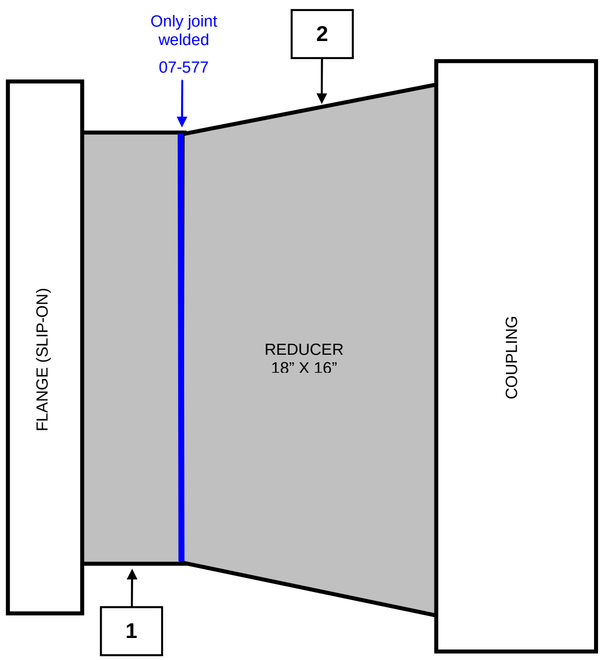
GENERAL DYNAMICS
nassco

WELDING ENGINEERING

04/23/07

16TH PRODUCTION PIPE WELDED BY HYBRID LASER

07/09/07



HOURS USED

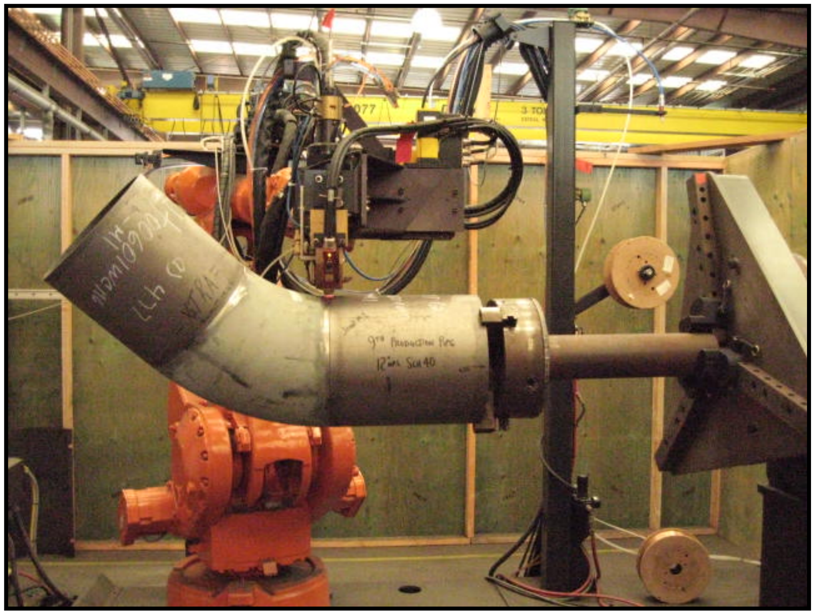
Set-up & machine one end of Reducer and pipe -------- = 1.5 Hrs
To grind and fit up (1) pipe joint by Pipe fitter ------------ = 0.7 Hr
Set-up and Weld (1) joints -------------------------------------- = 0.5 Hr
Repaired root pass, concavity 5" also fixed tie-end ---- = 0.5 Hr

3.2 HOURS TOTAL for (1 joint)

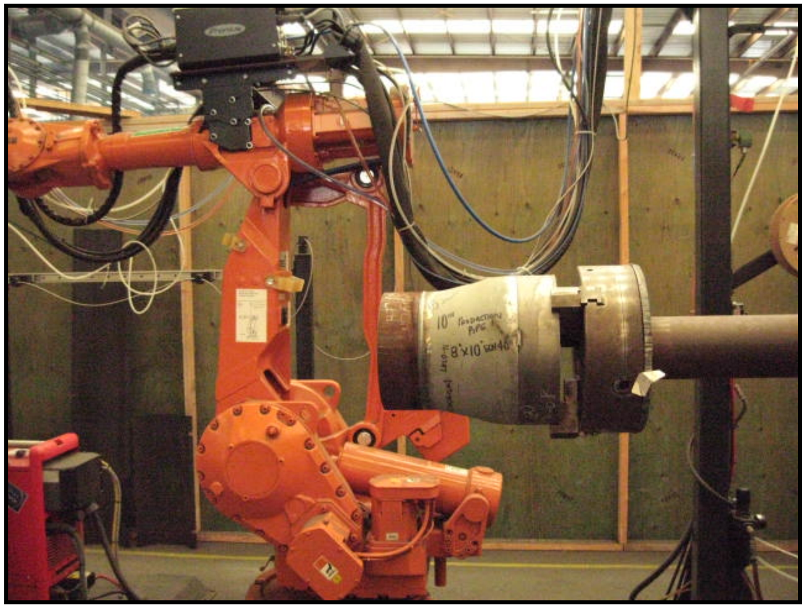
1. **16" NPS PIPE, SCH. 40 STEEL (90mm LENGTH) SAW CUT JOINTS, THEN MACHINED ONE END 90^0**
2. **18 x 16 NPS REDUCER, STEEL, MACHINED OFF BEVEL TO 90^0**

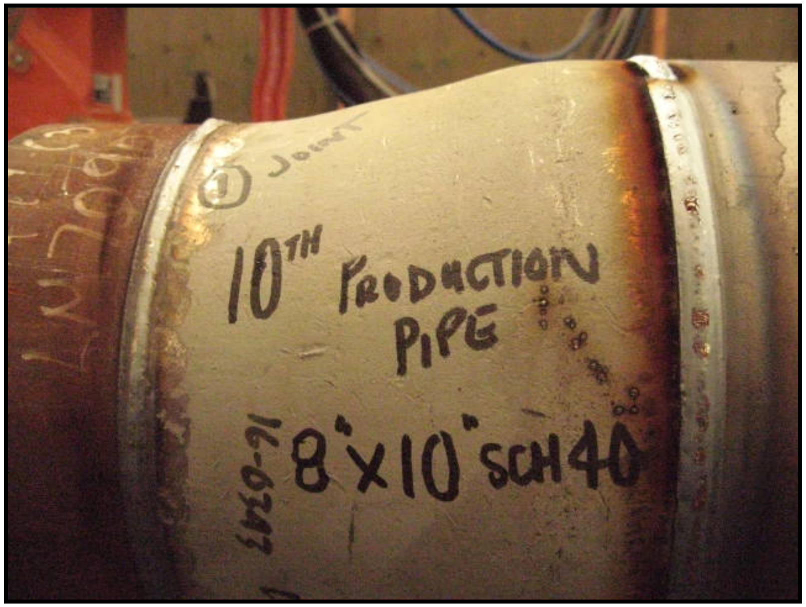
GENERAL NOTE:

SLIP ON FLANGE AND COUPLING WHERE INSTALLED AFTER LASER WELDING WAS COMPLETED

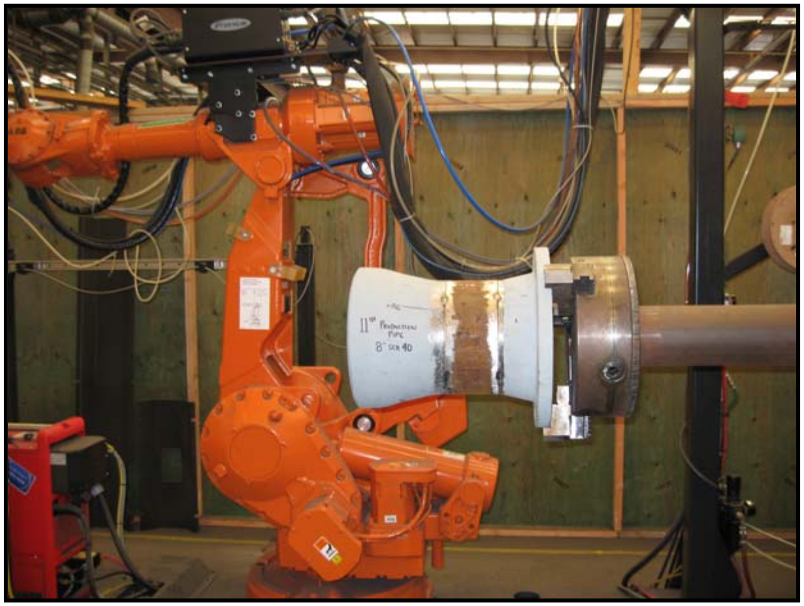


Ninth Production Pipe

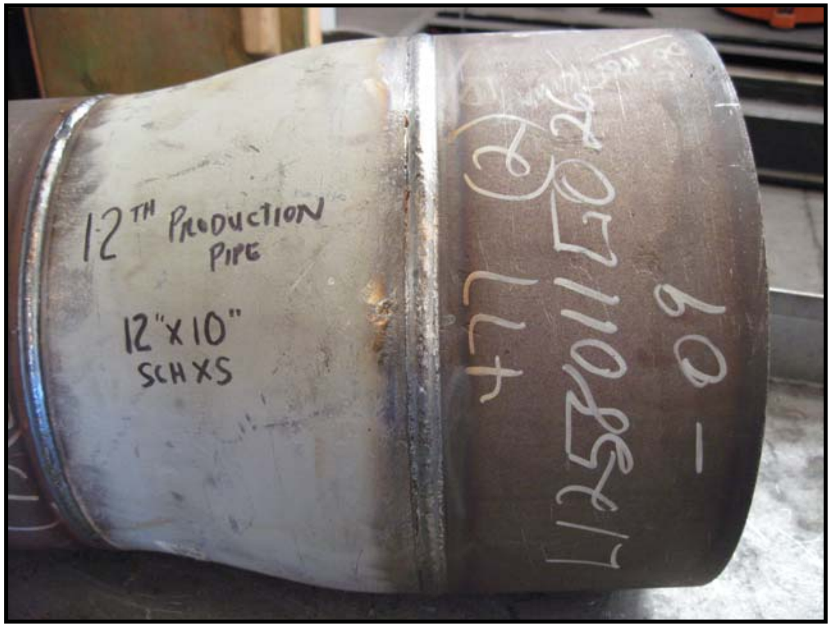




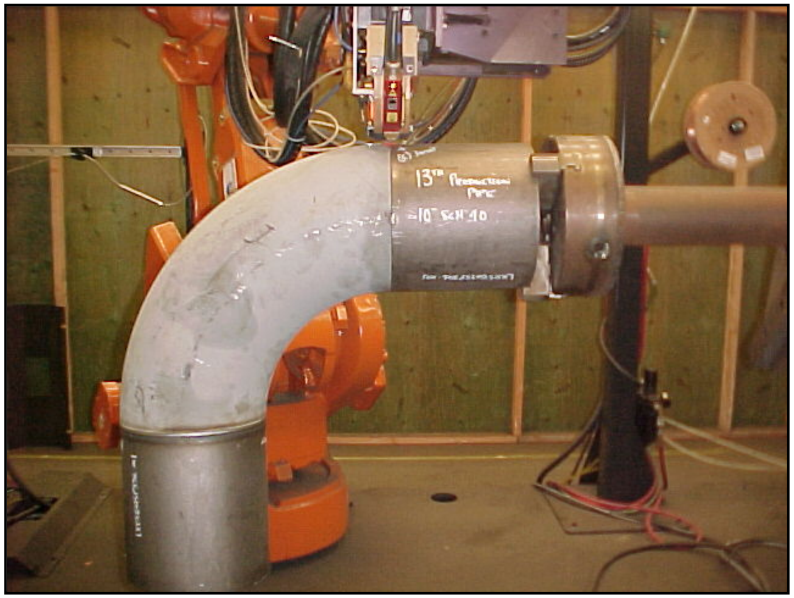
Tenth Production Pipe

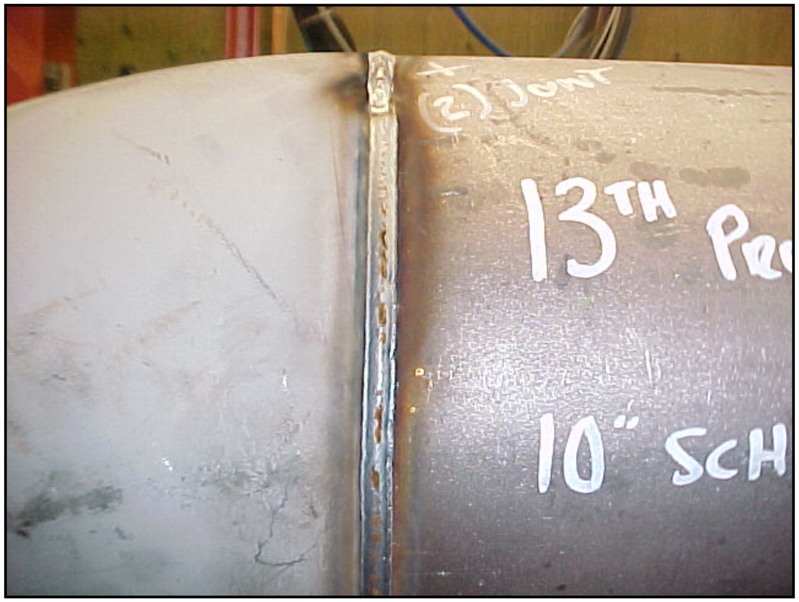


Eleventh Production Pipe

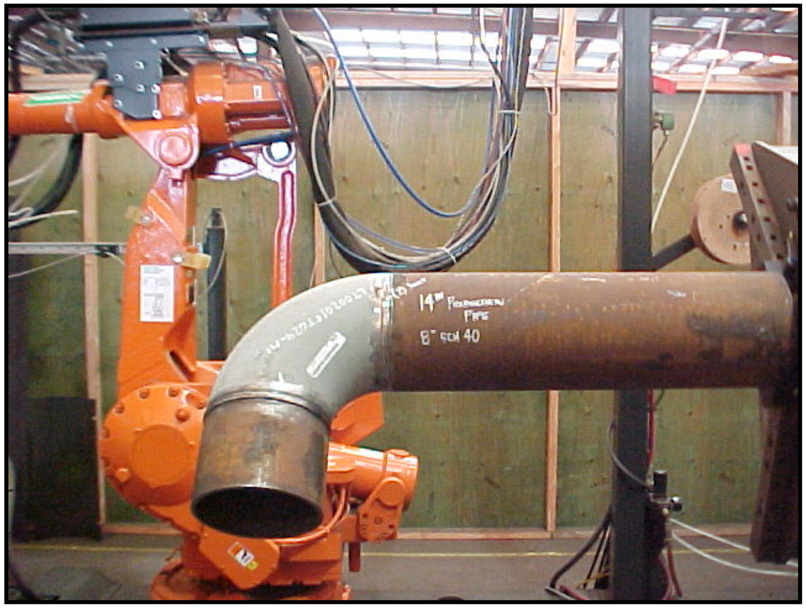


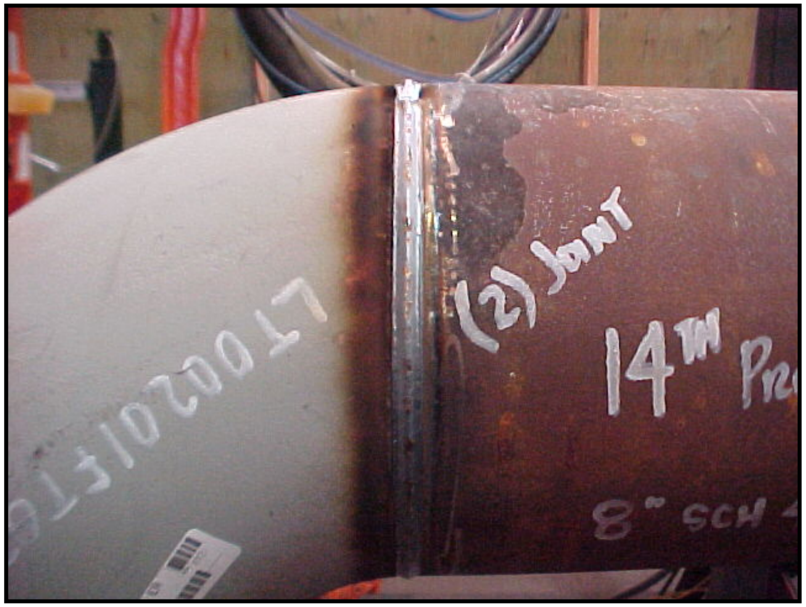
Twelfth Production Pipe



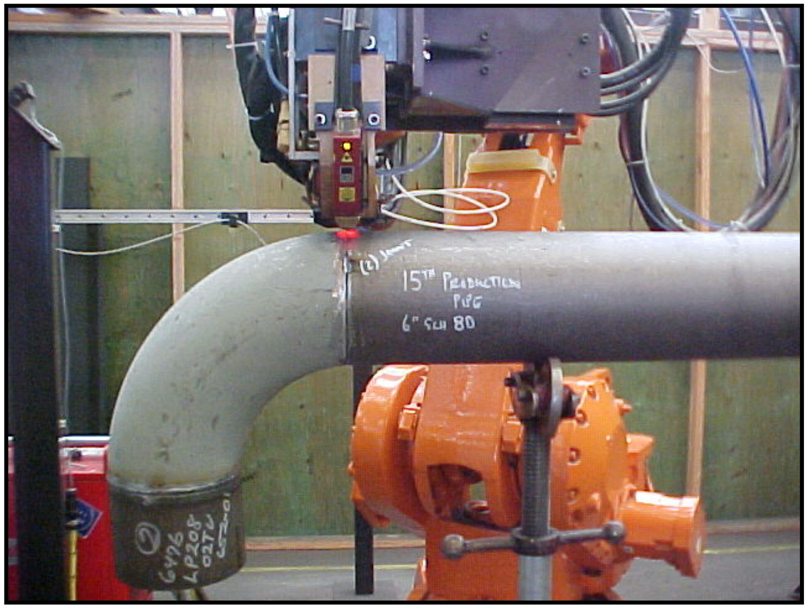


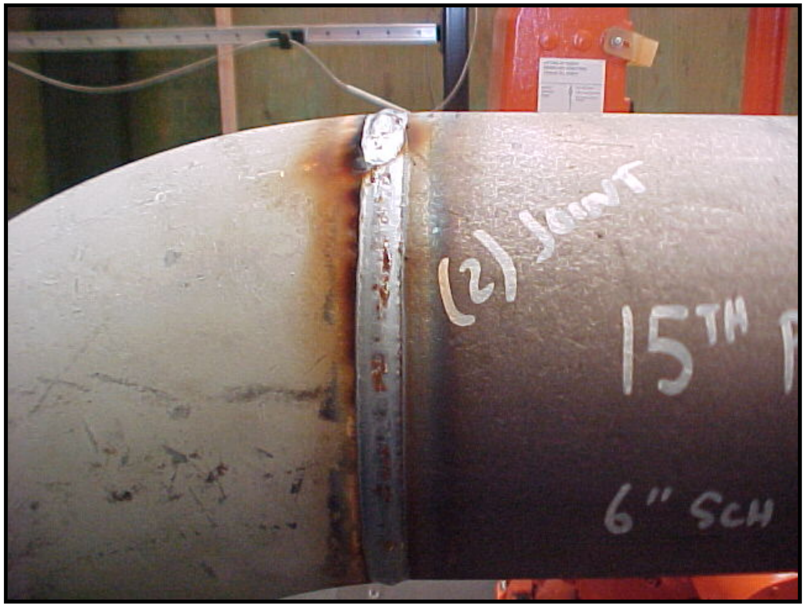
Thirteenth Production Pipe





14th Production Pipe





15th Production Pipe

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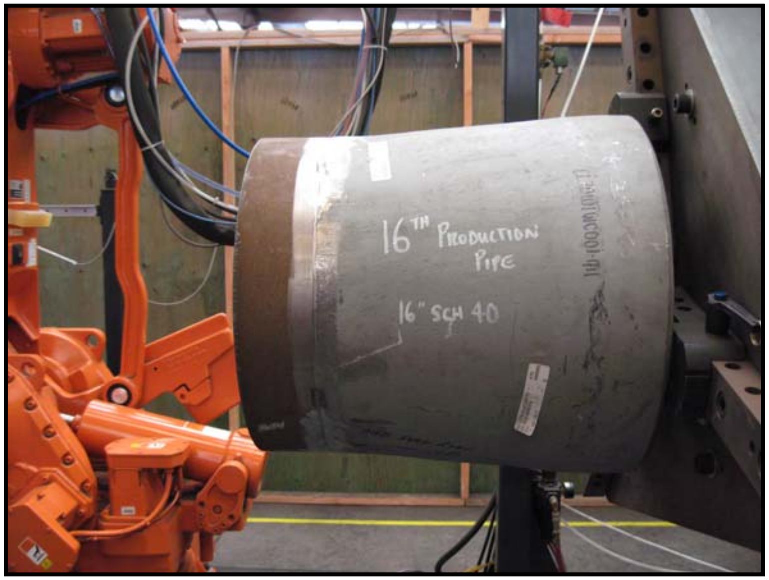

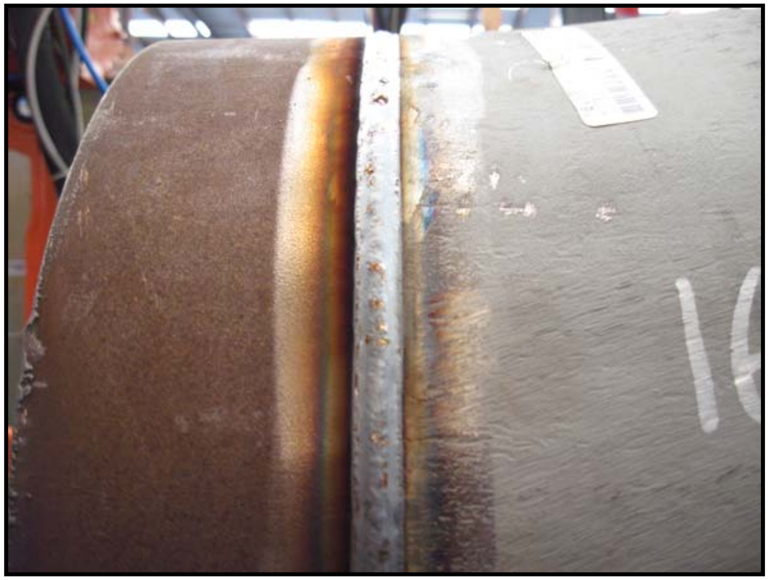

16th Production Pipe

APPENDIX D. Published Documents

The list below summarizes documents published during the course of this project.

- Reutzel, Kelly, Martukanitz, Bugarewicz, Michaleris, "Laser-GMA Hybrid Welding: Processing Monitoring and Thermal Modeling", *American Society of Materials (ASM)* Trends in Welding Conference Proceedings, Pine Mountain, GA, May 2005.

- Reutzel, Kelly, Tressler, Martukanitz, "Experimental Analysis of Practical Aspects of Hybrid Welding of Thick Sections", Proceedings of the 24th International Congress on Lasers and Electro-Optics Conference (ICALEO), Miami, FL, Paper No. 306, 10 pages, Oct 2005.

- Reutzel, Sullivan, Mikesic, "Joining Pipe with the Hybrid Laser-GMAW Process: Weld Test Results and Cost Analysis", American Welding Society (AWS) *Welding Journal*, v. 85, No. 6, pp. 66–71, Jun 2006.

- Reutzel, Kern, Tressler, "Continued Experimental Analysis of Practical Aspects of Hybrid Welding of Thick Sections", Proceedings of the 25th International Congress on Lasers and Electro-Optics Conference (ICALEO 2006), Paper No. 1906, 9 pages, Scottsdale, AZ, Oct 2006.

- Reutzel, Kern, Tressler, Sullivan, "Experience with Shipyard Installation of a Hybrid Pipe Welding System", Proceedings of the 26th International Congress on Lasers and Electro-Optics Conference (ICALEO 2007), Paper No. 1904, 10 pages, Orlando, FL, Oct 2007.

- Reutzel, Kelly, Sullivan, Huang, Kvidahl, Martukanitz, "Hybrid Laser-GMA Welding for Improved Affordability", Proceedings of the *Society for Naval Architects and Marine Engineers (SNAME)* Maritime Technology Conference and Expo and Ship Production Symposium, 11 pages, Ft. Lauderdale, FL, Nov 2007.